SAN FRANCISCO INTERNATIONAL AIRPORT RUNWAY RECONFIGURATION PROJECT

POTENTIAL FUTURE CONTRIBUTION OF AIR TRAFFIC MANAGEMENT TECHNOLOGY TO THE CAPACITY OF SAN FRANCISCO INTERNATIONAL AIRPORT

Report of the Independent Technology Panel

Prepared for

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San Francisco Bay Conservation and Development Commission

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Summary

In order to ensure that appropriate air traffic management technologies are considered in the environmental review process for the Runway Reconfiguration Project for San Francisco International Airport (SFO), the Airport and the San Francisco Bay Conservation and Development Commission (BCDC) agreed to form an Independent Technology Panel to identify viable technological capacity enhancements that may meet or approach the purpose and need of the project, and to provide an independent assessment of the potential impact of new technologies on the capacity of SFO. The Technology Panel was asked to evaluate the viability of potential improvements in air traffic control technology, airspace allocation, and aircraft navigation, surveillance, or communications technologies and the extent to which, alone or in combination with other measures, they may increase the capacity of SFO to address two of the project needs:

1. Reduce existing and projected flight delays
2. Accommodate projected flight demand.

It was agreed that the Technology Panel would focus on potential technologies to improve airfield capacity and/or reduce delays at SFO, and would recommend a suite of viable technological capacity enhancements to be included in the project alternatives (both build and no-build), as applicable. These recommendations would take into consideration the availability of technologies and their potential cumulative benefits to improve capacity or reduce delays at SFO.

The Panel members consisted of Capt. William B. Cotton of Cotton Aviation Enterprises, Inc., Mount Prospect, Illinois, John Foggia of Aviation, Navigation, and Satellite Programs, Inc., Chicago, Illinois, and Dr. Geoffrey D. Gosling of the University of California at Berkeley.

Issues to be Considered in Addressing the Potential Role of Technology

The Panel gave particular attention to a number of important issues that need to be taken into account in any consideration of the potential role of future air traffic management technologies in enhancing the capacity of SFO. The first issue is the operational constraints that arise from the existing runway layout and the operational configurations that are required to be operated in various weather conditions. The Panel recognizes that any significant reduction in air traffic delays with the existing runway configuration will require the ability to operate arrival traffic to two closely spaced parallel runways under instrument flight conditions. This is currently not possible with existing instrument landing and air traffic control technology. In addition, the need to provide gaps in the arrival stream to release departures on crossing runways means that arriving aircraft will need to be paired close together, as they are currently under visual flight conditions.

The Panel also considered a number of other issues that will affect the potential contribution of new technologies, including the time required to meet the certification and approval requirements, as well as install any necessary equipment on the aircraft fleet and train

the flight crews in the new procedures, the need to obtain stakeholder buy-in, and the uncertainties that result from the complex interaction of all these factors.

Review of Previous Studies

The Panel reviewed several previous studies that had been prepared for SFO, BCDC and others and that addressed the potential role of future air traffic management technologies at SFO, as well as a number of other relevant studies, including recent Federal Aviation Administration plans for the future evolution of the National Airspace System. While these studies identified most of the potential future air traffic management technologies that the Panel believes are applicable to SFO, the Panel found that the studies performed to date do not provide an adequate quantitative basis for assessing the future impact of these technologies on capacity and delays at SFO, and fail to clearly distinguish between the **operational capabilities** that will provide increased capacity and the **enabling technologies** that are required to implement these operational capabilities. In addition, many of the previous studies considered the various technologies in isolation and did not address how they could be combined to provide future operational capabilities that would enhance the capacity of SFO.

Conclusions and Recommendations

The Panel was asked to evaluate the prospects for air traffic management technology, airspace allocation, and aircraft navigation, control or communication technologies that could increase the capacity of SFO to reduce existing and projected flight delays and accommodate projected flight demand. The panel believes that technology related operational capabilities alone will not eliminate all existing and projected flight delays or fully accommodate long-term projected flight demand.

The Panel has identified a number of future air traffic management technologies that will enable operational capabilities that can increase the arrival capacity of SFO during poor weather conditions, and recommends that the following operational capabilities and their associated enabling technologies be considered in the environmental review process:

- Precision Runway Monitor with a Simultaneous Offset Instrument Approach procedure
- Required Navigational Performance
- Paired Approach procedure based on the use of Automatic Dependent Surveillance – Broadcast (ADS-B) for aircraft separation
- Wake Vortex Advisory System
- Use of Center TRACON Automation System tools and ADS-B to increase the arrival capacity of a single runway.

These operational capabilities vary with respect to both the likely capacity increase that they can provide and the timing when they are likely to be available. Those operational capabilities that will become available between now and 2005 appear likely to offer only modest increases in capacity with the existing runway configuration. As additional operational capabilities become available further in the future, they will enable larger increases in capacity.

Furthermore, with several of these technologies, the increase in capacity that they provide depends on the extent to which aircraft are equipped to take advantage of them and flight crews are trained in and able to fly the necessary procedures. Therefore the capacity increase that they provide will initially be fairly small, and will increase over time as more aircraft are equipped and flight crews able to take advantage of the procedures.

Even so, it does not appear that the operational capabilities that will become available between now and 2010 will close the gap between the good weather and poor weather capacity. At best, it appears that by 2010 the arrival capacity of the existing runway configuration might be increased to about 45 aircraft per hour from the current 30 aircraft per hour. However, this will only be possible for some poor weather conditions. For other weather conditions, the increase will be much less. More advanced operational capabilities that could become available in the 2010 to 2015 time frame offer the potential to further increase the poor weather arrival capacity of the existing runway configuration under a wider range of poor weather conditions. By 2015, it may be possible to achieve an arrival rate to closely spaced parallel runways of as many as 60 aircraft per hour under most poor weather conditions.

The operational capabilities and their associated enabling technologies that the Panel recommends be included in the environmental review of the Runway Reconfiguration Project differ for the No-Build and Build Alternatives. This distinction is not completely clean, since two Build Alternatives retain the closely spaced parallel runways in the north/south direction. Since arrivals on the Runway 19 pair during Southeast Plan operations only occur a small percentage of the time, consideration should be given to whether the costs of implementing an operational capability that allows simultaneous instrument arrivals to both Runway 19L and 19R for Alternatives A-3 or BX-2 are justified by the delay reduction benefits. This cannot be determined without a much more detailed analysis than has been performed to date or the Panel had the time or resources to undertake.

The capacity benefits from any given set of technologies depends on both the traffic characteristics at the time and the extent to which the aircraft fleet is equipped to take advantage of them and the flight crews are trained in and comfortable with the necessary procedures. Therefore an adequate assessment of the likely increase in capacity from any particular set of operational capabilities in some future year will require a much more detailed analysis than the Panel has had either the time or the resources to perform. In order that the potential contribution of future air traffic management technologies can be properly addressed in the environmental review process, a quantitative assessment of both the likely capacity benefits of the various operational capabilities identified by the Panel and the associated uncertainties will need to be made. This assessment could be undertaken in parallel with other parts of the process and will need to consider the operational context within which the various technologies might be deployed as well as the extent to which the various technologies complement each other.

The Panel believes that SFO is in a strong position to take an active leadership role in the deployment of new air traffic management technologies, and that such actions will make a big difference in how quickly potential future capabilities become available. The Panel recommends that SFO formally engage in a strategic technology initiative to accelerate the deployment of new air traffic management technologies. This would build on its current efforts to deploy PRM/SOIA and could be coordinated with similar efforts by other airport authorities.

POTENTIAL FUTURE CONTRIBUTION OF AIR TRAFFIC MANAGEMENT TECHNOLOGY TO THE CAPACITY OF SAN FRANCISCO INTERNATIONAL AIRPORT

1. BACKGROUND

San Francisco International Airport (SFO) is proposing to reconfigure its airfield in order to better address its current and future operational requirements, and requires approval from the Federal Aviation Administration (FAA) and other federal, state and regional agencies in order to do so. One such agency is the San Francisco Bay Conservation and Development Commission, which under California state law is required to issue a permit to enable any filling of the San Francisco Bay to occur. The City and County of San Francisco Planning Department's Office of Environmental Review (OER) and the FAA are acting as lead agencies under the California Environmental Quality Act (CEQA) and the National Environmental Policy Act (NEPA), respectively, to prepare a joint Environmental Impact Report/Environmental Impact Statement (EIR/EIS). The EIS must be complete before the Airport Commission can consider adopting a reconfiguration alternative, and the FAA can consider approval of a revised Airport Layout Plan that incorporates the proposed reconfiguration or any SFO requests for federal funding or passenger facility charges to finance the reconfiguration.[1] The EIR/EIS must contain an analysis of reasonable alternatives to the proposed airfield reconfiguration adopted as the preferred alternative by SFO, and the information provided by the EIR/EIS will be used by other agencies in making their decisions regarding SFO's requests for permits or other approval actions.

The FAA and the OER have identified the overall Purpose and Need of the Runway Reconfiguration project as follows:

> *The purpose of the proposed improvements to SFO is to* ***reduce existing and projected flight delays*** *and accommodate existing and anticipated aircraft, as well as* ***accommodate projected flight demand****, thereby achieving efficient airport operations* ***under all weather conditions*** *while addressing the airport's goal of reducing human exposure to noise.*

Alternatives under consideration that meet this purpose and need include:

- Technological enhancements that would improve the arrival and departure capacity of SFO during a variety of weather conditions.
- Demand management techniques to reduce the number of flights in and out of SFO to a level closer to its adverse weather capacity.
- Reconfiguring the SFO runway system to increase its capacity in all weather conditions.

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[1] San Francisco International Airport, *SFO Runway Reconfiguration Program, EIR/EIS Environmental Review Process,* Status Summary 2, November 2000.

In order to ensure that appropriate air traffic management technologies are considered in the EIR/EIS process, SFO and the San Francisco Bay Conservation and Development Commission (BCDC) have agreed to form an Independent Technology Panel to identify viable technological capacity enhancements that may meet or approach the Purpose and Need of the Runway Reconfiguration Project, and to provide an independent and expert assessment of the impact of new technologies on the capacity of SFO. It was agreed that the panel should consist of three members. One panel member would be designated by SFO and one panel member designated by BCDC. These two panel members would identify and agree on a third member, who would chair the panel. The membership of the panel was finalized in late April 2001 and the panel members commenced work on May 2.

This report presents the findings and conclusions of the Panel.

Scope of the Panel

The formal terms of reference of the panel that were agreed by SFO and BCDC are included as Attachment A. This section summarizes the scope of the panel's charge and the approach adopted.

The Technology Panel was asked to evaluate the viability of potential improvements in air traffic control technology, airspace allocation, and aircraft navigation, surveillance, or communications technologies and the extent to which, alone or in combination with other measures, they may increase the capacity of SFO to address two of the project needs:

1. Reduce existing and projected flight delays
2. Accommodate projected flight demand.

It was agreed that the Panel would focus on potential technologies to improve airfield capacity and/or reduce delays at SFO, and would recommend a suite of viable technological capacity enhancements to be included in the project alternatives (both build and no-build), as applicable. These recommendations would take into consideration the availability of technologies and their potential cumulative benefits to improve capacity or reduce delays at SFO.

As part of the Runway Reconfiguration Project, SFO has already undertaken a number of studies on the causes of weather delays at the airport, and the potential use of various technologies to reduce these delays. Other studies on potential technologies that could reduce delays at SFO have been undertaken as part of the recently completed update of the Bay Area Regional Airport System Plan and by consultants to BCDC. The panel was asked to undertake an independent review of these previous work efforts, and to recommend any additional technologies that it considers viable to be implemented within a realistic timeframe relative to the proposed SFO project. The panel was directed to focus its analysis on technologies anticipated to be available within the 2005 – 2015 project horizon. For each technology recommended for consideration in the EIR/EIS, the Panel was asked to identify what stage of development the technology currently is in, any associated technology dependence requirements, required regulatory or other approvals, status of pilot and air traffic controller acceptance, purchase costs, required training for implementation, and any other potential risks associated with the technology.

The Panel was instructed to take account of the time frames and risks normally associated with the implementation of new technologies in air traffic operations, and to use the following guidelines in assessing the viability of potential technologies:

- The technology concept must be proven
- The FAA will have to certify the technology as safe and consistent with the National Airspace System
- Manufacturers must design, build, and certify any required equipment
- If the technology requires ground equipment, the siting of such equipment may require approval under NEPA, CEQA, and other environmental regulations
- If the technology requires equipment installation in aircraft, the equipment, installation and training must be certified for each type of aircraft.

The panel would be expected to prepare a report that would summarize its findings and recommendations, and comment on the previous technology work products already prepared for SFO. The report would discuss any differing analyses in the various studies already prepared as part of SFO's ongoing analysis, as well as studies performed for the Regional Airport Planning Committee and BCDC. Finally, the panel was expected to offer its suggestions as to which technologies should be considered as part of the "no-build" alternatives for analysis in the EIR/EIS, with an assessment of their potential cumulative benefits to improve capacity at SFO, and which technologies should be considered as part of the "build" alternatives for analysis in the EIR/EIS, with an assessment of their potential cumulative benefits to improve capacity at SFO.

Capacity Issues at SFO

Since the purpose of the Panel is to examine the potential of air traffic technologies to enhance capacity at SFO and reduce weather-related delays, some discussion of capacity issues at SFO is in order. Before discussing the specific attributes of the runway configuration at SFO, several points should be noted:

1. The capacity of the runway system at any airport depends on the operating configuration (which runways are being used for landings and takeoffs), the weather conditions, the mix of aircraft using the airport (since the required separation between any two aircraft depends on their wake category), the air traffic procedures in use, and the proportion of arrivals and departures. Since these factors all change during the course of a day, the capacity varies as well, even for a specific operating configuration.
2. Delays increase as demand in any hour approaches capacity, and grow disproportionately when demand is greater than capacity for prolonged periods. Since demand typically varies through the day, the magnitude of the delays that result when weather causes an airport to switch from one operating configuration to another depend on when during the day this occurs.
3. There are two different ways to define delay. One is the difference between the scheduled arrival and departure time of a flight and the time when it actually arrives or departs. The other is the difference between the time that a flight actually takes to go

from its departure airport to its destination and the time that it would take if there were no congestion in the system. Airlines can reduce the first type of delay by putting additional time in the schedules. However, this reduces productivity with a consequent increase in operating costs and results in inconvenience to the passengers on days when delays do not occur.

4. When delays start to increase at an airport, the FAA will generally implement a ground delay program in which some flights are held on the ground at their origin airport for a time. Because of the time that it takes for aircraft to fly to their destination, the FAA tries to predict when the capacity will change at an airport several hours in advance and adjust the flow accordingly. This has two consequences. One is that flights may be delayed at one airport due to a capacity problem at another. Thus some of the observed delays at an airport are due to capacity problems at other airports. Indeed, flights often arrive late at airports even in good weather. The second is that if a ground delay program is in effect and the weather improves earlier than expected, many flights will generally have been delayed unnecessarily.

5. During periods of high delay, airlines typically cancel some flights, both to reduce the delay to their other flights and to minimize the ripple effect as delays propagate through their network. Canceling flights during periods of high delay reduces the delay to later flights in the schedule, but may increase the delay experienced by the passengers on the cancelled flights, depending on when they are able to get another flight. Thus simply measuring the delays experienced by aircraft may understate the delays experienced by the passengers.

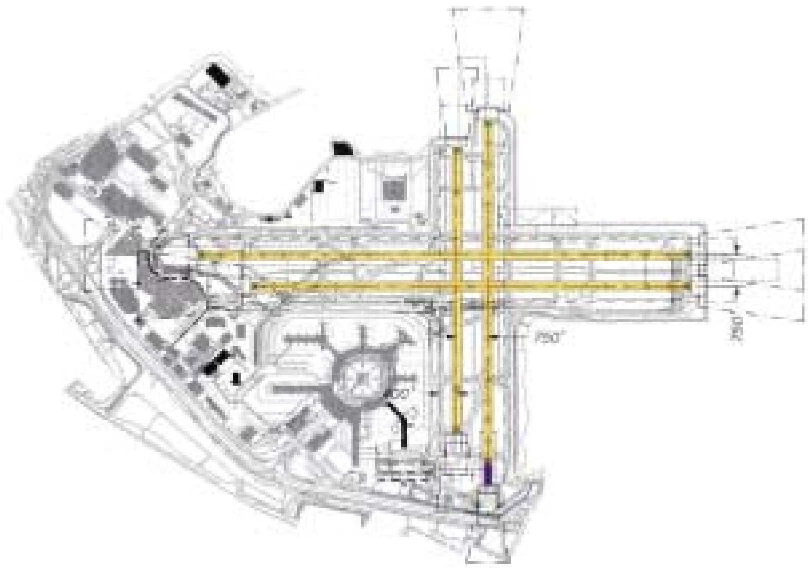
These factors affect the way that runway capacity and delay is measured, and need to be borne in mind when interpreting the results of any analysis of capacity or delay at an airport.

Existing Runway Configuration at SFO

The existing runway configuration at SFO is shown in Figure 1-1. The airport has two pairs of parallel runways separated by 750 feet that intersect at right angles. The resulting runway interdependence is the driving factor that influences the capacity under all operating configurations. Under the most common weather conditions, aircraft arrive on the Runway 28 pair and generally depart on the Runway 1 pair. Some aircraft that need a long runway, such as long-haul international flights, depart on Runway 28 right (28R). This keeps all the arrivals and most of the departures over the Bay. Because of the intersecting runways, the arrivals to Runways 28 left (28L) and 28R are generally paired during busy periods in order to create a gap in the arrival stream to allow a pair of aircraft to depart on Runways 1 left (1L) and 1 right (1R). This gap is typically between about 3.6 and 4.2 miles, which provides enough time for one pair of landing aircraft to cross the intersection, and a pair of departing aircraft on 1L and 1R to be released and cross the intersection before the next pair of arriving aircraft on 28L and 28R reach the end of the runways.

One important consequence of this mode of operation is that procedures to reduce the separation between successive pairs of aircraft may increase arrival capacity, but prevent any departures from being released. Also the use of Runway 28R by a departure can result in the loss of two arrivals or two departures, depending when it is released in the arrival sequence. If this departure is a heavy aircraft,[2] which it typically is, then the required separation by following aircraft may result in the need for a larger gap than usual, which further reduces capacity. Thus any technology to increase good weather capacity must address this need to coordinate arrivals and departures.

Figure 1-1 **Existing SFO Runway Configuration**



Under less than ideal weather conditions, the situation becomes more complicated. If the winds are from the west and too strong to allow departures on the Runway 1 pair, due to aircraft crosswind limitations, then the departures have to be interleaved with the arrivals on the Runway 28 pair. Since each arrival or departure blocks the subsequent operation on the same runway until it has exited the runway or taken off, rather than simply crossed the intersection, this reduces the runway capacity under visual flight rules (VFR) by 15 arrivals per hour. If cloud or poor visibility on approach prevents aircraft from achieving visual contact with each other while they are still safely separated, they cannot be paired and only one arrival stream is possible to any of the runway pairs.[3]

The operating configurations with aircraft arriving on the Runway 28 pair are referred to as West Plan. When winds are from the south or east, as they often are during winter storms, then the arrival flow has to be changed to land on the Runway 19 pair and depart from the 10 pair. This operating configuration is referred to as Southeast Plan. This also keeps the arriving and departing aircraft over the Bay, but because the distances to the runway intersections for aircraft landing on the Runway 19 pair are less than for aircraft landing on the Runway 28 pair, the arrival capacity is slightly higher. However, this configuration is often associated with low ceiling and visibility, when only one arrival stream is possible. If the winds from the east are too

[2] Defined as an aircraft with a maximum gross takeoff weight greater than 255,000 pounds. Most widebody aircraft used in long-haul international operations, such as the Boeing 747 or 777, are in this class.
[3] This is true for approaches from all four directions.

strong to allow arrivals on the Runway 19 pair, due to aircraft crosswind limitations, then both arrivals and departures have to use the Runway 10 pair. This brings the arrivals in over the high terrain to the west of the airport, creating a significant noise impact on the communities under the approach path as well as reducing the capacity, due to the need to interleave arrivals and departures and the use of only one arrival stream.

A final operating configuration, that fortunately is rarely needed, occurs when winds from the north are too strong to allow landings on either the Runway 28 pair or the Runway 10 pair. Under these circumstances, aircraft have to land on the Runway 1 pair, and either depart on the Runway 28 or 10 pair if the crosswind permits, or be interleaved with the arrivals on the Runway 1 pair. However, high terrain to the south of the airport prevents an instrument approach from that direction, so aircraft have to approach from the east or west using the instrument landing system (ILS) on Runways 28R or 10L and then circle to land once they have achieved visual contact with the airport.

The consequence of these various operating configurations is that the capacity of SFO varies widely with different weather conditions, and typically is cut in half during poor weather, when only one arrival stream can be used. As will be discussed later, this loss of arrival capacity during poor weather accounts for the majority of the delay experienced by flights to SFO that is due to capacity limitations at SFO, rather than inadequate capacity at other airports or other causes (such as aircraft mechanical problems). Thus any air traffic technology solution that is intended to reduce delays at SFO must be capable of significantly increasing arrival rates during poor weather.

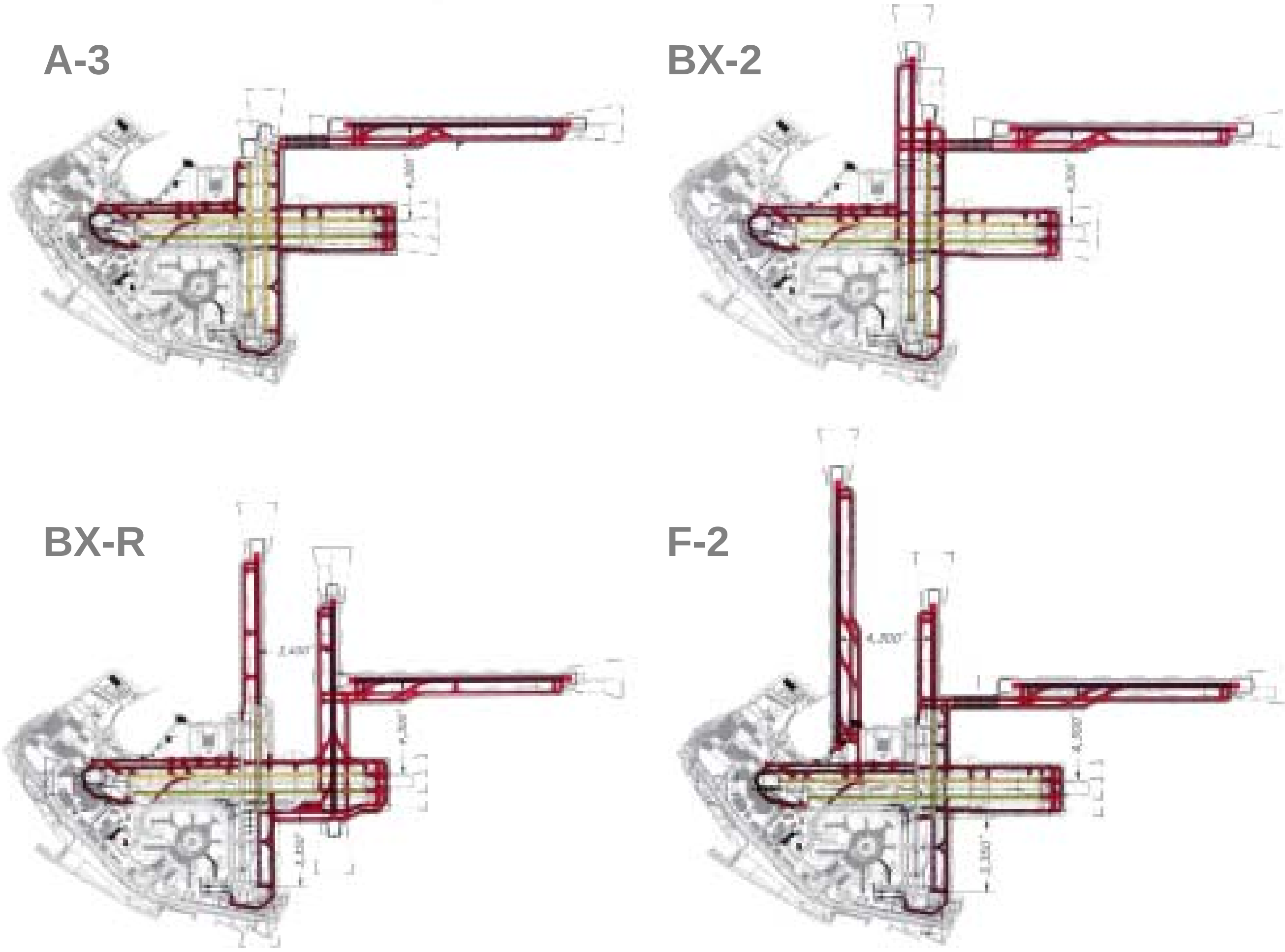
It is also worth noting that departure capacity at SFO during poor weather is not currently a significant problem, since the departure capacity of the closely spaced runway pairs under instrument flight rules (IFR) is generally much higher than the arrival capacity. Aircraft can be released simultaneously on two closely spaced runways, as long as they can maintain visual contact until they are turned onto departure courses that diverge by at least 15 degrees. This can typically be done once aircraft reach 400 feet above the ground. Thus simultaneous departures can be performed with relatively low cloud ceilings. Furthermore, over a period of an hour or more there is generally no need to have the departure capacity much higher than the arrival capacity, since more aircraft cannot depart than have arrived. However, if a particular air traffic technology increases the arrival capacity during poor weather, then consideration must be given to whether there is enough departure capacity to handle the increased flow of traffic.

Proposed Runway Reconfiguration Alternatives

When the Panel commenced its work, the SFO Runway Reconfiguration Program had defined four alternative runway configurations that were being studied in the EIR/EIS process, as shown on Figure 1-2. Each of these alternatives involves different runway capacity issues.

All four alternatives involve constructing a new runway parallel to and 4,300 ft. to the north of the existing Runway 10L/28R (which would then be designated 10C/28C). The new Runway 10L/28R and Runway 10C/28C would be the primary arrival runways and would support simultaneous independent arrivals in all weather conditions. The existing Runway 10R/28L would be retained as a departure runway under some wind and cloud conditions.

Figure 1-2 **Proposed SFO Runway Reconfiguration Alternatives**



The four alternatives differ in terms of the changes to the north-south runways:

- Alternative A-3 proposes to leave the existing runways unchanged.
- Alternative BX-2 would extend the existing Runway 1L 4,500 ft. to the north and Runway 1R 1,000 ft. to the north, increasing the ability of heavier aircraft to use these runways.
- Alternative BX Refined (BX-R) would extend the existing Runway 1R 6,500 ft. to the north, convert the existing Runway 1L/19R to a taxiway, and construct a new Runway 1R/19L 3,400 ft. to the east of the existing Runway 1R/19L (which would be redesignated 1L/19R). The 3,400 ft. separation will allow simultaneous arrivals to Runways 19L and 19R under IFR conditions with the use of a Precision Runway Monitor (PRM) radar.

- Alternative F-2 would incorporate the same changes to the existing Runway 1/19 pair as Alternative BX Refined, together with a new Runway 1L/19R 4,300 ft. to the west of the existing Runway 1R/19L and far enough to the north to avoid intersecting Runway 10C/28C.

All four alternatives would achieve a significantly increased IFR arrival capacity under West Plan flow, due to the ability to maintain simultaneous arrival streams to both Runway 28C and 28R. There would also be a significant increase in VFR arrival capacity under West Plan, since the arrival stream to Runway 28R would no longer need to have gaps to allow departures to take off on the Runway 1 pair. The West Plan arrival capacities would vary slightly between alternatives, due to differences in the need for gaps in the arrival stream to Runway 28C to accommodate departures.

Alternatives A-3 and BX-2 would see no increase in arrival capacity under Southeast Plan flow. Departure capacity would be increased, due to the ability to release departures on Runway 10L without the need to wait for gaps in the arriving traffic. However, this increase is of limited value if the airport capacity is constrained by the arrival capacity. Alternative BX Refined would see a significant increase in IFR arrival capacity under Southeast Plan flow, due to the ability to maintain simultaneous independent arrival streams to Runways 19L and 19R. However, the separation between the runways would reduce the ability to release departures on Runway 10C, and the situation could arise in which it might become necessary to temporarily reduce the arrival rate in order to allow more departures to be released on Runway 10C. Finally, Alternative F-2 would see the same increase in IFR arrival capacity under Southeast Plan flow as Alternative BX Refined, provided the arrival stream to Runway 19R is not constrained by airspace interactions with arrivals to Oakland Airport to the north.

Apart from interactions between operations on intersecting runways, a further constraint on operations with the proposed runway reconfiguration alternatives is the presence of Mount San Bruno to the northwest of the airport. This constrains the location of the new Runway 10L/28R due to the need to meet missed approach clearance surface requirements for aircraft landing on Runway 28R under IFR conditions.

In early August 2001, as the Panel was completing this report, SFO announced that it had decided to drop Alternative F-2 and replace it with a new alternative termed Alternative BX-6. This alternative is very similar to Alternative BX-R, but moves the north/south runways to the south and changes some taxiway locations in order to reduce the amount of Bay fill required. The Panel does not believe that these changes significantly change its assumptions or alter its conclusions.

Potential New Technologies – Issues to be Considered

The potential role of new air traffic management technologies to reduce existing and projected flight delays at SFO and to accommodate projected flight demand has been the subject of a number of previous studies, that are discussed in more detail later in this report. Each of these studies has mentioned many of the technologies that have been proposed to date to reduce the delays at SFO, although the treatment of each technology differs among the reports in several respects, such as the level of detail, the likely operational readiness date, and the potential benefit provided. However, a common failing of most of these studies is their focus on the particular technologies rather than the operating capability that each technology enables. This section discusses the implementation issues that need to be considered in order for any meaningful discussion of the potential contribution of any particular technology. The importance of considering these issues in order to understand what will be required to implement any new technology is increasingly being recognized at a national level.[4]

The Panel has been charged with evaluating potential technological improvements that might:

1. Reduce existing and projected flight delays
2. Accommodate projected flight demand.

It has already been established that the delays at SFO are largely caused by the arrival acceptance rate of the airport, particularly when weather precludes the simultaneous use of two landing runways. Therefore, the discussion in this section will focus on the implementation issues of systems proposed to improve the arrival rate under reduced ceiling and visibility conditions.

Enabling Technologies and Operational Systems

The Panel believes that it is critically important to maintain a distinction between enabling technologies and operational systems. In this discussion, an “operational system” refers to the combination of equipment, both ground-based and airborne, and the procedures for the use of that equipment that will increase the throughput (arrival and/or departure rate) of the runway system at SFO. In this context, an “operational system” need not necessarily be called a system, but is understood to include whatever is needed to achieve a specified operating capability. For example, the use of a Precision Runway Monitor (PRM) with a Simultaneous Offset Instrument Approach procedure, discussed later in this report, constitutes an operational system designed to achieve an increase in arrival acceptance rate in the West Plan configuration from 30 to approximately 38 aircraft per hour with cloud ceilings from 1,600 feet to 3,500 feet. The enabling technologies and procedures for this system are a PRM, an offset localizer with glide slope, a Precision Approach Path Indicator (PAPI), a monitor control position, procedures, and pilot and controller training. The PRM alone provides no capacity benefit.

Another example of the distinction between an operational system and an enabling technology is precision navigation and its use in supporting new standards for reduced aircraft separation from obstacles or other traffic. The system name for this capability is Required Navigation Performance (RNP). The operating capability enabled by RNP is the ability to safely fly closer to obstacles, and potentially to other aircraft, in instument meteorological conditions (IMC). The definition of RNP does not specify the technologies for achieving a given RNP value. As a practical matter, most operators are using the global positioning system (GPS) in combination with other navigation elements to achieve the RNP required in a given airspace or procedure. The GPS element only provides value by enabling participation in a more efficient flight procedure or access to certain airspace. RNP provides the operating capability to achieve specified performance benefits, as a total system.

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[4] Transportation Research Board, *Expediting Implementation of Air Traffic Management System Improvements*, Transportation Research E-Circular Number E-C031, Washington, D.C., May 2001.

Dependencies

An increase in airport arrival or departure rates has been shown to result from various operational system implementations. Those systems contain multiple elements of ground or airborne hardware, software, procedures, training, and approvals. If the design of a system is completely known, many of the steps to its implementation can proceed in parallel. Usually, however, some of the elements are more mature than others, but total system readiness is dependent on each element being complete and successful. For example, Automatic Dependent Surveillance – Broadcast (ADS-B) is a surveillance system with both airborne and ground-based elements. With the system operating, air traffic control can provide separation, sequencing and spacing services where conventional radar coverage does not exist. Air-to-air separation responsibility can also be designed around ADS-B. In the first case, the operating system is dependent upon both airborne and ground-based systems being in place, approved, and the operating personnel trained. In the second, the dependency on the ground element is eliminated, reducing the technical risk of delayed implementation, but requiring approval of new systems and procedures.

Implementation of any given operational system is not just dependent on the technology elements all being in place. Dependencies for the successful deployment of the system include:

- Funding for the overall program
- Certification of airborne elements
- Commissioning of ground elements
- “Buy-in” of the stakeholder groups representing the users and operators of the system
- Operational approvals and training
- Necessary environmental approvals, and
- System integration, testing and validation to prove that the system performs its intended function as designed with the desired performance.

Historically, the performance of the enabling technologies has not held up major system deployments. More often it has been funding or buy-in by the stakeholders that has delayed or killed major aviation programs. For example, Reduced Vertical Separation Minima (RVSM) was pursued for 33 years before finally being implemented in the North Atlantic airspace. The technology that enabled the required height-keeping performance by aircraft was available decades before, but funding the equipment installations, achieving stakeholder buy-in, and gaining the necessary approvals spanned several careers. Similarly, the Microwave Landing System (MLS) was technically ready for several decades before its eventual demise in the U.S. before implementation, due to lack of stakeholder (airline) buy-in.

Evaluating proposed system dependencies will include not only technical dependencies of systems, but also the broader acceptance, approval, and availability of funding for deployment. This requires a strong “will” to succeed among the entire aviation community.

Timing

Timing is similar to dependencies in that it relates to bringing together multiple system elements – in some cases representing totally separate disciplines – at the same time. This practically never happens, of course, resulting in "shelf life" considerations for the items completed ahead of the operational readiness date. The "better" often becomes the enemy of the "good" in this scenario, as fast moving technologies outpace total system development. "Requirements creep" can occur in which actions intended to improve the performance or capability of a system under development actually delay deployment as the system elements are changed, redesigned, and re-tested.

Sometimes, funding is mistimed, either being available before it is needed, but gone when the need arises, or not available until too late, after the design or engineering team is re-assigned. Funding mistiming is especially acute when it is from public sources where long lead times are the norm compared to funding by private enterprises.

Timing the introduction of systems to be used in air traffic operations can also be influenced by established meeting intervals, charting publication dates, the commissioning of new air traffic facilities such as the Northern California TRACON, or the completion of local or regional airspace re-designs. Effective program management must consider each of these when preparing a realistic timeline for development and deployment.

Uncertainties

The introduction of new technologies to improve airport operations necessarily involves many organizations, several of which are not under the control of the program managers. Approvals, stakeholder buy-in and funding usually fall into this category. This fact introduces a great deal of uncertainty into a program timeline. It is generally not possible to simply assign resources and be assured of a successful outcome. Often, the successful involvement of outside parties is a function of persuasive power, negotiation skill or sheer persistence – each quite different from classical program management. It is rare to find a program manager skilled in all the disciplines required to implement a new air traffic operating capability. It takes a very broad base of experience, both technical and political skills, a great deal of persistence and the willingness to deal with a lot of uncertainty.

Often it boils down to "moving ahead because the cause is just and the obstacles to success will be overcome". Uncertainties can be assessed and assigned a numerical value based on educated judgment from similar experiences. These values represent the risk of the program not being completed as planned. This is different from the risk of it not being completed at all, which is generally based on a broader policy decision. The uncertainties create a measure of the likelihood that the schedule will slip to the right, delaying the operational readiness date of a new system beyond the date at which the underlying technical requirements can be met.

Culture for Change

Humans are by nature resistant to change. Change is disruptive and uncomfortable when not self-directed. The introduction of new operating capabilities to airport operations involves just such change, triggering negative responses from the great majority of those who must use the new systems and procedures, even when they ultimately may feel the change has benefited them personally. The introduction of the Traffic Alert and Collision Avoidance System (TCAS), an airborne collision avoidance system now deployed on all commercial passenger jet aircraft, suffered greatly from this syndrome. Air traffic controllers were sure it would disrupt their working lives and create chaos in the airspace. Pilots did not trust the system to perform as designed and thought that it might solve one conflict, but create another. Now, after a decade of normal use and the elimination of mid-air collisions wherever TCAS is required, most airline pilots would not fly without it. Numerous ATC and pilot errors around the world have been prevented from becoming serious incidents or accidents because of TCAS.

Nevertheless, the resistance to change is as strong as ever. Our culture in the aviation industry is "risk averse". This not only means averse to the risk of an accident, which is good, but it can also mean averse to the risk of program slip or failure, which can kill a program before it even starts. In a risk averse management culture, the status quo is protected vigorously and programs for change are saddled with insurmountable hurdles to success. Some of these hurdles are insistence on the elimination of uncertainty, a return on investment of under a year, "off the shelf" technology readiness, and prior endorsement by all stakeholders. Unfortunately this aversion to program risk stifles innovation, resulting in lower efficiency and productivity, and is overcome easily only during times of war or national crisis, when managers will accept program risk over an even greater apparent threat if nothing is done.

With respect to the capacity of San Francisco International Airport, a degree of "crisis" is apparent to most decision makers. While all of the symptoms of risk aversion still exist, there does appear to be a reasonable chance for success in adopting some change to correct the problem.

Interaction with Other Strategies

Although the role of the Panel is to address the potential contribution of future air traffic control technologies to increasing the capacity of SFO, it should be borne in mind that deploying these technologies does not preclude pursuing other strategies to reduce delays, such as adopting measures to increase average aircraft size or to shift certain operations to other airports, or constructing new runways. Thus the use of any new technology should be viewed as part of a set of development scenarios that combine these different strategies in various ways. By enhancing the capacity of a particular runway reconfiguration, the use of new technologies will minimize the need for demand management measures to reduce the delays that arise whenever demand exceeds capacity. The Panel believes that the deployment of new air traffic management technologies should be aggressively pursued to enable the airport to achieve the highest throughput that can reasonably be achieved with either existing or future runway configurations, considering the costs and benefits of each new technology.

However, this is not simply a matter of performing a separate analysis for each strategy in isolation and then adding the resulting capacity increases together. The benefits obtained from deploying a given technology will be affected by any measures that change the nature of the demand, just as they will depend on the runway configuration to which they are applied. Thus each combination of measures must be analyzed as a package.

Structure of this Report

The remainder of this report consists of four sections. The following section presents and discusses the findings of the review of the previous studies of potential capacity technologies that were reviewed by the Panel. Section 3 then discusses the operational capabilities that are required in order that new air traffic technologies can result in an increased capacity. As noted above, technology alone does not increase capacity. Rather, any given technology must be combined with new or modified procedures and associated operating rules that allow the air traffic control system to handle a greater volume of traffic. Section 4 then examines the various potential technologies that the Panel believe offer some prospects for increasing capacity at SFO within the timeframe being considered, and discusses why those technologies that were not considered likely to affect the capacity at SFO were rejected. For each of those technologies that the Panel felt should be given further consideration, the section examines the nature of the capacity contribution provided by the technology, assesses its potential effect on capacity at SFO, explores the implementation considerations that would have to addressed, and discusses the likely risks involved. Finally Section 5 presents the conclusions and recommendations of the Panel and identifies the air traffic operational technologies that the panel believes should be included in the EIR/EIS analysis for both the "no-build" and "build" alternatives, as well as the additional steps that need to be taken to fully assess the potential contribution of these technologies and pursue their implementation.

2. REVIEW OF PREVIOUS STUDIES

The panel was asked to undertake a review of six previous studies that examined the causes of weather related delays at SFO and potential technologies that could increase the capacity of SFO or reduce delays. Three of these studies were prepared for SFO, one for the FAA and OER, one for the Regional Airport Planning Committee, and one for BCDC. In addition, the Panel reviewed a number of other relevant studies that are discussed briefly at the end of this section.

Reducing Weather-Related Delays and Cancellations at SFO

The results of a detailed study of the causes of weather-related delays at SFO undertaken by Charles River Associates and the John F. Brown Company were published in April 2000.[5] The study examined in some detail the frequency of occurrence of arrival delays and flight cancellations at SFO during a three-year period from 1997 to 1999, as well as the distribution of the duration of those delays. The study assembled data on the weather conditions at SFO for each hour during the period, and analyzed the differences in delays with varying weather conditions, as well as how the traffic flow management system resulted in differences in delays experienced by flights from different parts of the country. The study also presented and discussed a number of strategies to reduce weather-related delays and cancellations with the existing runway configuration, and commented on the prospects for increasing arrival capacity through the use of new technology.

The study focused on delay to arriving flights and defined delay in terms of the actual arrival time relative to the flight schedule. While this is certainly how most travelers think of delay and how the U.S. Department of Transportation defines on-time performance, it is not the only way to measure delay and does not address the issue of how much additional time the airlines have allowed in their schedule for anticipated delays. Thus changes in the number and duration of arrival delays from year to year could be due in part to changes in airline scheduling

[5] Charles River Associates Incorporated and John F. Brown Company, *Reducing Weather-Related Delays and Cancellations at San Francisco International Airport*, Prepared for San Francisco International Airport, April 2000.

practice. Also, to the extent that delays are anticipated in airline schedules, those delays impose real costs on the airlines, even though they do not appear in the delay data used in the study.

The study noted that SFO experiences two different types of weather that can result in significant levels of arrival delay. The first is low stratus cloud that often forms over the San Francisco Bay in the late afternoon or evening and dissipates some time the following morning (commonly referred to locally as "fog"). The other type of adverse weather are storms, that usually occur during the winter, mostly between November and March, and are associated with rain and low cloud. These storms often last all day, and may even last for several days at a time. They are also often associated with southerly winds that require the airport to be operated with landings to the south or east rather than the west. The study therefore classified each day during the three-year period into one of five categories: good weather all day, bad weather in the morning, bad weather all day, bad weather in the afternoon or evening only, and all other conditions.

During the three-year period for which detailed delay data was available, good weather occurred all day for 50 percent of the days. Bad weather in the morning occurred on 29.5 percent of the days, bad weather all day occurred on 14.6 percent of the days, and bad weather in the afternoon or evening or other conditions each occurred on about 3 percent of the days. However, the days with bad weather in the morning accounted for 36 percent of the bad weather hours and 40 percent of the ground-hold delay on bad weather days.[6] Days with bad weather all day accounted for 56 percent of the bad weather hours and 55 percent of the ground-hold delay on bad weather days. Thus over half of the weather-related delays are associated with bad weather all day, which mostly occurs during winter storms. The study also showed that the extent of the delays experienced during bad weather in the morning in very dependent on when the low stratus clears. If this has not occurred by 10 am, the delays start to build rapidly, and if it has not occurred by noon, then extensive delays and cancellations result. Analysis of the hour when the bad weather cleared on days with bad weather in the morning during a four-year period from 1996 to 1999 showed that this had occurred by 10 am on 50 percent of the days and by noon on 85 percent of the days. Therefore it is clear that a high proportion of the delays experienced at SFO occur on about 30 percent of the days in the year – those when low stratus occurs in the morning and does not clear until late morning or early afternoon, and those when bad weather occurs all day, typically during winter storms.

The study also examined how delays were distributed across flights from different regions of the country. It was found that flights from the western part of the United States, defined as an area from the Albuquerque, Denver and Salt Lake City Air Route Traffic Control Centers to the West Coast, had significantly more cancellations and higher delays during bad weather than flights from the rest of the country. The study suggested that this is the result of two factors. The first is the consequence of FAA policies on which flights are issued ground holds when SFO experiences bad weather. Because of the unpredictability of when the weather will improve, the FAA tends to issue ground holds to flights from airports closer to SFO, since these can reach SFO more quickly once the weather improves and the ground hold is lifted. The second factor is the interaction of ground holding with airline decisions on which flights to cancel through a process known as Collaborative Decision Making (CDM). Because ground

[6] Technically these delays are referred to as Expected Departure Clearance Time (EDCT) "where-caused" delays, and measure the aircraft-minutes of delay incurred by airlines at other airports due to conditions at SFO.

holds disrupt not only the flight being held, but also any subsequent flights during the day that would be operated with that aircraft, the airlines are more likely to cancel short-haul flights in high frequency markets, in order to preserve as much of their schedule integrity later in the day as they can, and also because by canceling some flights, they may be able to accommodate those passengers on later flights that operate at more or less the same time the delayed flight would have, had it not been cancelled. However, the net effect of this is that travelers in West Coast markets bear a disproportionate share of the burden of cancellations and delays.

Discussion of Capacity Enhancing Technologies

Although the study did not primarily address how air traffic technologies could increase capacity, it did discuss the potential benefits of the planned introduction at SFO of a new procedure known as Simultaneous Offset Instrument Approach (SOIA) that uses Precision Runway Monitor (PRM) equipment to allow instrument approaches to occur on both Runways 28L and 28R during low stratus conditions with ceilings as low as 1,600 feet. No estimates were made or discussed of the likely effect on delays of this technology. The study also discussed in broad terms several other technologies, including precision radar and Global Positioning System (GPS) satellite navigation systems, and reported that these had been discussed with the FAA, researchers at MIT Lincoln Laboratory, and United Airlines. It was noted that these discussions indicated that certain of these measures have the potential to increase the bad weather arrival capacity at SFO to some extent, but that the individuals with whom the report authors had spoken believed that the potential of some measures that had been proposed in the press had been greatly overstated. In view of the lack of specificity in the report as to which technologies had been discussed, who the discussions had been with within each organization, or what exactly those individuals had said, it is unclear how much weight can be put on these findings. Beyond these discussions, it does not appear that the authors of the report undertook any independent assessment of what those technologies might in fact be able to achieve.

Impact on Air Travelers

In addition to the detailed statistical analysis of weather and flight delay data, the study also examined the impacts of these delays on air travelers through a series of focus groups and a survey of SFO air travelers. The results of this aspect of the study are largely anecdotal and qualitative, although some data was collected in the survey of the duration, reason, and consequence of the most recent serious delay experienced at SFO by the respondent. It is unclear how representative these responses are, and there was no attempt in the report to compare the length of delays reported in the survey to the statistical data on flight delays.

Runway Reconfiguration Project Working Papers

Potential air traffic control technology enhancements are discussed in two working papers prepared by P&D Aviation for the Runway Reconfiguration Project.[7,8] Both working papers contain identical sections with different titles -- called "Future ATC Technology" in

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[7] P&D Aviation in association with Turner Collie & Braden, *Analysis of SFIA Runway Reconfiguration Impact on Regional Air Transportation Systems*, Working Paper No. 7: Identify and Evaluate Technology Trends, Prepared for San Francisco International Airport, Oakland, California, March 1999.

[8] P&D Aviation, *Analysis of SFIA Runway Reconfiguration Impact on Regional Air Transportation Systems*, Working Paper No. 12: Delay Reduction Alternatives, Prepared for San Francisco International Airport, Oakland, California, March 1999.

Working Paper No. 7 and "Operational Enhancements" in Working Paper No. 12. Seven "ATC System" technologies are described and their opportunities for use at San Francisco discussed in a qualitative fashion. The descriptions of these technologies are generally brief but accurate as of two and a half years ago when the working papers were written. The discussion of opportunities for use at SFO does not really address how they might be used, with the exception of the discussion of Simultaneous Offset Instrument Approach (SOIA) procedures. The discussion of other technologies cites experience at other locations and lists implementation risks but offers no specific estimates of potential benefits. The seven systems discussed are:

- Precision Runway Monitor (PRM)
- Simultaneous Offset Instrument Approach (SOIA) Procedures
- Center-TRACON Automation System (CTAS)
- Local Area Augmentation System (LAAS)
- Closely-Spaced Parallel Approach Procedures
- Wake Vortex Detection and Prediction Systems
- New Generation Ground Hold Algorithms

The last of these, new generation ground hold algorithms, is correctly identified as "not explicitly designed to be a delay reduction alternative." Therefore, it will not be discussed in this report. The first, PRM, is correctly said to have relevance in San Francisco only in combination with Simultaneous Offset Instrument Approach (SOIA) procedures. The report states that FAA had no plans to fund the PRM at SFO and suggested that the airport or airlines would have to. Of course, that is what is now taking place.

<u>SOIA</u>

Of all seven systems, the SOIA procedures get the most attention in the working papers. However, half of the description is of expanded visual approach procedures, not SOIA, and it is stated that "the amount by which SOIA procedures would increase availability of dual approaches at SFO relative to existing visual approach procedures has not been conclusively determined". Later, in the discussion of the opportunities for use, SOIA is said to permit an arrival rate of 45 landings per hour, "a greater proportion of time". Subsequent simulation by staff at the Bay TRACON has predicted that a maximum arrival rate of 38 aircraft per hour is more likely with SOIA in use.[9] Discussions with air traffic controllers have indicated that visual approaches are only used down to a ceiling of 3,500 feet, not 2,100 feet as stated in the working papers, even though visual approaches are "approved" to the lower ceiling. Controllers have found it too difficult to establish visual separation prior to losing radar separation at the lower ceiling values.

A more recent description of SOIA procedures at SFO prepared by United Airlines and the FAA[10] indicated that with SOIA, arrival rates are expected to increase from 30 to 37 per hour during conditions that occur on 10-15% of operating days. Of course, these are the same days that now experience the greatest amount of total delay.

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[9] Discussion with staff at Bay TRACON.
[10] *Examining Technologies that Improve Operations in San Francisco*, Powerpoint presentation to the Independent Technology Panel prepared by Dave Jones, United Airlines, and Ken Peppard and George Greene, Federal Aviation Administration.

The working papers are not clear on when SOIA might be available. It is said to be either "in the near term future" or "uncertain". It now appears to be about one year away.

CTAS

The CTAS description is superficial and no longer up to date with respect to the Final Approach Spacing Tool (FAST). The tool in place at Dallas/Fort Worth International Airport (DFW) is pFAST, the "Passive" FAST. While correctly pointing out that greater opportunity exists for improvement using this tool at DFW than SFO, the discussion of opportunities for use at SFO does not mention that the Traffic Management Advisor (TMA), another component of CTAS, and pFAST could be used to help pair airplanes by weight category and space them correctly on the respective final approach courses during the use of SOIA procedures. This automation would have the effect of improving the performance of individual controllers, perhaps bringing the arrival rate of 38 aircraft per hour up to 40 or 41 during the periods of SOIA use. This application is not currently used in the Dallas installation and could well require some additional programming in addition to the site-specific modification that would be required for any CTAS implementation at SFO.

As an unmodified tool for controllers, the CTAS elements do not increase the maximum capacity of the airport, but could more consistently deliver this capacity in any given time period, resulting in a greater throughput.

LAAS

This discussion of LAAS in the working papers is misleading because LAAS is an enabling technology, not an operating capability. LAAS is described as "the standard high precision landing navigational aid in the future". It is an element of that system but it will not stand alone. LAAS and GPS together provide the signals to be used by aircraft, ultimately to allow landings in Category III weather conditions. They can also provide the very precise navigational performance necessary to support participation in RNP routes and procedures as well as to resolve inter-airport conflicts.

While citing GPS/LAAS activities at other airports, no specific applications for SFO or benefits to be derived from their use are mentioned. Since this report was written, the standards for LAAS have matured. A public-use LAAS signal at Chicago O'Hare International Airport (ORD) is already being broadcast. Full commissioning is expected in the fall of 2002.

Closely Spaced Parallel Approaches

The description of the FAA/NASA work on closely spaced parallel approach procedures provides a minimal amount of information. Dependence on the enabling technologies GPS/LAAS, ADS-B, and Cockpit Display of Traffic Information (CDTI) is noted. No description is given of how these would be integrated or any discussion provided of what procedures could be derived to assist SFO operations. It is only stated that it is "unlikely that these procedures will provide meaningful reductions in aircraft delays at SFO until the long-term future, if at all." It is true that much needs to happen prior to this capability being implemented at SFO, but this combination of technologies does represent the only way to achieve full IMC operations on the two existing runways simultaneously.

Wake Vortex Detection and Prediction Systems

The description of this technology gives the FAA more credit than is due. The FAA has not been "developing advanced radar systems to detect and warn pilots of potentially dangerous wake vortices". NASA has pursued a program called the Aircraft Vortex Spacing System (AVOSS) that uses wind and weather measurements to predict whether a vortex will present a hazard to a following airplane. Additionally, some contractor work on a real-time vortex tracking system called SOCRATES is proceeding under NASA funding.

The discussion of opportunities for use at SFO is correct in describing how these systems could provide more efficient use of the runways than today, although does not provide specific numbers for the likely increase in capacity. A wake vortex prediction system could decrease average spacing on each approach and help resolve safety concerns resulting from the risk of an aircraft on one approach encountering the wake from an aircraft on the parallel approach. The working papers describe the availability of this technology as the mid-to long-term future, although it is unclear what this means.

Summary

In summary, the working papers list most of the technologies known at the time they were written that can contribute to increased capacity in San Francisco. Except for the SOIA description, they attribute benefits to technologies rather than the operating capability those technologies enable. Benefits are listed only qualitatively, so it is not possible to estimate their impact on SFO operations either singly or in combination.

Estimates of the year of availability of the technologies are given only in the broadest terms, such as near term, mid to long term, or very long term. No definitions of these terms in years are given. There are no specific recommendations regarding which technologies to support or pursue from either a timing or value viewpoint.

FAA/OER Analysis of New and Emerging Technologies

The Panel reviewed a preliminary draft of a Federal Aviation Administration report[11] that surveyed a variety of potential technologies, and commented on their development status and applicability to SFO. Included in the report were discussions on the Precision Runway Monitor (PRM), GPS and its augmentations, Required Navigation Performance (RNP), Automatic Dependent Surveillance – Broadcast (ADS-B), Airborne Information for Lateral Spacing (AILS), wake vortex detection, Center/Terminal Radar Approach Control Automation System (CTAS), civilian tiltrotor aircraft, and noise cancellation technology.

The report describes the current ILS technology installed at SFO, which it considers state-of-the-art, but notes that this cannot support dual parallel approaches under instrument conditions. In discussing new and emerging technologies that could address this limitation, the report notes that many of them are components of the FAA National Airspace System (NAS) Modernization Plan, although it emphasizes that nearly all these technologies are still under development or are as yet unproven concepts, and describes many of the uncertainties involved in assessing their final implementation configurations or timing.

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[11] Federal Aviation Administration, *San Francisco International Airport Runway Reconfiguration Program EIR/EIS – New & Emerging Technologies*, Preliminary Report, November 2000.

The report notes that *implementation* of a capability is significantly different than *introduction* of the technology, and *certification* of systems takes several years, while user equipage can take a substantial period of time – on the order of five or more years after the decision to equip a fleet is made.

The FAA/OER document states, "… the likelihood that these technologies will provide substantial delay reduction at SFO and will be implemented within a reasonable timeframe is low". However, the report failed to consider the various technologies as a *suite* or system of technologies, acting as enablers of capacity benefiting capabilities. Separate consideration of each technology led to the conclusion that, taken by themselves, they would provide little or no capacity improvement at SFO.

Another limitation of the report is that it only discusses the application of the various technologies to the *existing* runway configuration at SFO. Since the greatest limiting factor on SFO capacity is the combination of runway spacing and intersection dependencies, it is not surprising that this limited approach to the application of new technology did not appear to offer much increase in capacity.

The discussion of the use of PRM/SOIA with SFO's existing closely spaced parallel runways indicates that this should give an improvement of seven operations per hour during those periods when it can be applied, i.e., when the ceiling is between 1,600 feet and 3,500 feet and the visibility is 4 miles or greater.

With respect to GPS and its augmentations – the Wide Area Augmentation System (WAAS) and the Local Area Augmentation System (LAAS) – the report provides a good assessment of schedules and applications, noting that WAAS is behind schedule relative to its CAT I capability, and is primarily applicable to en route navigation and non-precision approach. WAAS is not now expected to be able to achieve instrument landing capability to Category I minima for the foreseeable future, but should be able to provide lateral navigation/vertical navigation (LNAV/VNAV) capability to 350 foot ceiling and one mile visibility minima. LAAS is described as being on schedule. The report states that LAAS will provide straight-in guidance, like ILS, and therefore will not contribute directly to an increase in capacity. However, while LAAS will provide ILS-like straight-in guidance, it will also provide position/velocity/time (PVT) inputs to aircraft navigation systems for terminal area maneuvering. Although helping to maintain predictable, repeatable paths in space, this does not by itself overcome the difficulties with closely spaced runways or alleviate intersection dependencies.

However, LAAS coupled with ADS-B can improve pairing to the runways and help allay aircrew concern over paired approaches when descending through a stratus layer. The report does not mention Cockpit Display of Traffic Information (CDTI) in its discussion of ADS-B. LAAS/ADS-B/CDTI comprise a system with capabilities to provide capacity enhancements, particularly if runway configuration changes are implemented, and to further aircrew situational awareness during SOIA operations.

AILS also requires LAAS/ADS-B/CDTI to function properly. The report correctly states that this technology is as yet unproved for a runway spacing below 2,500 feet. During trials in Minneapolis to runways 3,300 feet apart, the system worked flawlessly, and exhibited significant promise. For runways closer than 2,500 feet apart, AILS is likely to require a wake vortex advisory system (WVAS) in order to safely allow simultaneous arrivals.

The report discusses the need for wake vortex detection to operate closely-spaced approaches and reduced in-trail separations. The NASA research efforts to develop an Aircraft Vortex Advisory System (AVOSS) described in the report form the predictive component of a wake vortex advisory system, and will need to be coupled with a wake monitoring system to ensure aircrew and controller buy-in. However, development of these systems is continuing, and a concept of operations for the use of a wake vortex advisory system in air traffic control is currently being developed by NASA.

The report provides a good summary of the CTAS suite of capabilities – Traffic Management Advisor (TMA), Final Approach Spacing Tool (FAST), Descent Advisor, Surface Movement Advisor (SMA), and Departure Planner. These tools provide automated guidance to air traffic controllers and will facilitate the en route-to-terminal coordination and routing/pairing/metering tasks. The report gives estimates of potential capacity increases that the tools might provide at SFO that were made by NASA personnel on the basis of the experience at Dallas/Fort Worth International Airport (DFW). The situation at DFW is not directly comparable to SFO because of significant differences in runway configuration and spacing, and it is unclear how these differences were taken into account. Even so, these estimates suggest that significant improvements in capacity with the existing runway configuration are not expected from CTAS. Although safety and the efficient use of airspace would be enhanced, the existing runway configuration will limit any capacity gains. Discussions between the Panel and Bay TRACON managers indicated that SFO was dropped from consideration as an early CTAS implementation site because of the existing runway configuration limitations on throughput.

The report suggests that civilian tiltrotor aircraft and noise cancellation technology are unlikely to contribute to capacity enhancement at SFO by 2015. Although tiltrotor aircraft could eventually serve some short-haul West Coast operations, in view of the problems being encountered deploying the V-22 Osprey the Panel agrees that it is unlikely that a large commercial tiltrotor aircraft will be available for public use much before 2015. While noise cancellation technology, if it proves technically feasible, could help reduce some of the community noise impacts of operations at SFO, this will not contribute to an increase in capacity in a technical sense, although it may make an increase in operations at SFO less unpopular with the surrounding communities.

Regional Airport System Plan Update

As part of the latest Regional Airport System Plan (RASP) Update undertaken by the Regional Airport Planning Committee (a joint committee formed by the Metropolitan Transportation Commission, the Association of Bay Area Governments, and the Bay Conservation and Development Commission, that includes representatives of the major airports in the region and other aviation stakeholders), a sensitivity analysis was undertaken of the factors affecting airport demand and capacity in the region, that included an assessment of the benefits of new air traffic control technology.[12] This study provides a short description of each technology considered, together with a brief qualitative assessment of the potential application of the technology to increasing the airport and airspace capacity in the region. The study also

[12] Metropolitan Transportation Commission, Roberts, Roach & Associates (R2A), Keiser and Associates, and Vince Mellone, *Sensitivity Analysis of Factors Affecting Airport Demand and Capacity (including alternatives to new runways)*, Chapter 6 "Potential Benefits of New Air Traffic Control Technology", (revised August 2000) *in* Regional Airport Planning Committee, *Regional Airport System Plan Update 2000*, Volume III, February 2001.

briefly discusses the role of the FAA flow control program in managing delays and the potential that improvements in weather forecasting and greater collaboration with airlines in managing air traffic delays could reduce airport delays. However, no assessment is made of the magnitude of these delay reductions. The study notes that questions had been raised (presumably during the RASP Update process) about the possible impact of New Large Aircraft on runway and airspace capacity, and states that preliminary wind tunnel tests performed by Airbus Industrie (the manufacturer of what was then designated the A3XX aircraft) indicate that the wake vortices would be about the same as a Boeing 747 aircraft. No source is given for this statement, nor is there any discussion about the implications for capacity if "about the same" turns out to require larger in-trail spacing than current standards.

Technologies Considered

The study discusses the following technologies:

- Wide Area Augmentation System (WAAS)
- Local Area Augmentation System (LAAS)
- Automatic Dependent Surveillance – Broadcast (ADS-B)
- Center-TRACON Automation System (CTAS)
- Required Navigation Performance (RNP)
- Precision Runway Monitoring (PRM)
- Simultaneous Offset Instrument Approaches (SOIA)
- Wake Vortex Detection and Avoidance

The report notes that the WAAS augmentation to the Global Positioning System (GPS) navigation system is intended for en-route navigation and Category I instrument approaches, and states that while it will improve Bay Area air traffic operations through shortened flight time en-route, improved cockpit situational awareness, reduced oceanic separation minimums, and more flexibility in selecting user-preferred routes, it will not reduce delays at SFO. The report notes that the LAAS augmentation to GPS will provide the necessary accuracy and integrity for Category II/III precision approaches to all runways at airports where it is installed, and states that coupled with a Precision Runway Monitoring system, it could permit simultaneous Category II/III approaches to parallel runways separated by at least 3,000 feet. The report indicates that whether LAAS and PRM will permit a reduction of runway separation standards below this remains undetermined.

The discussion of ADS-B (Automatic Dependent Surveillance – Broadcast) describes the operation of the system and notes that while this could be a component of a system to reduce lateral aircraft spacing that would include improved wake vortex detection, it will not in itself increase capacity for parallel instrument approaches. The discussion of CTAS describes the functional capabilities of two of the CTAS tools, the Traffic Management Advisor (TMA) and Passive Final Approach Spacing Tool (pFAST). The report states that CTAS will improve the efficient flow of arrival traffic to the Bay Area airports and should benefit runway capacity by reducing excess spacing between aircraft. However, the report notes that the benefits at SFO are limited because of the need to allow sufficient gaps in the arrival stream to enable aircraft departures on the crossing runways. Having stated that CTAS should be able to increase capacity by reducing excess spacing, the report then states that CTAS will not in and of itself increase the instrument approach capacity at SFO. This contradiction in the report is left unresolved by the omission of any analysis of how much excess spacing might be reduced at SFO.

The report describes the application of RNP for instrument approaches into Juneau Airport, Alaska, but does not explain the underlying concept of RNP, or how it might be applied in the Bay Area. It states that a combination of RNP and PRM could theoretically permit simultaneous instrument approaches at SFO down to Category I or II minima, but states that this would require resolving a number of issues, including GPS reliability, aircraft transgressions from the approach course, and wake vortex hazards. There the discussion ends. In view of the obvious potential benefits that such a procedure would offer, it is clear that further study in these areas is warranted.

The report provides a brief description of the PRM system and discusses the introduction of this system at Minneapolis-St Paul International Airport in 1997, that demonstrated the ability of the system to support simultaneous instrument approaches to runways spaced 3,000 feet apart with the use of an offset instrument landing system (ILS) localizer. The report notes some flight crew concerns about the safety of these procedures, due to lack of training or equipment limitations. The report states that PRM will not in and of itself improve the IFR capacity at SFO without a major change in the required spacing between parallel runways. This statement is immediately contradicted by the following discussion of the SOIA procedure, which does precisely that and is being implemented at SFO. The report notes that the Draft Environmental Assessment for the SFO SOIA project predicts an increase in IFR approach capacity during weather conditions when it can be operated from about 30 to 38 arrivals per hour. The report notes that these conditions occur about 7 percent of the time, but does not discuss how the occurrence of delays corresponds to when these conditions occur. The report notes that the Air Line Pilots Association (or at least one of its members) has expressed concerns about the safety of the proposed procedure, but does not pursue this aspect any further or discuss why the FAA would continue to implement the proposed procedure if it did not believe that these concerns could be resolved.

The final technologies discussed in the report are a project at SFO by NASA Langley Research Center to develop sensors and instruments to detect, locate and track aircraft wake turbulence, and an approach being developed by Boeing Aircraft Company to design aircraft wings to reduce the strength of the wake vortex behind an aircraft. The discussion of both efforts is rather vague and that of the Boeing concept appears incomplete. It is unclear from the discussion how promising either technology is. The report makes no mention of a major NASA research program directed at aircraft wake vortex detection, the Aircraft Vortex Spacing System.

Capacity Benefits Assessment

Apart from the assessment of the capacity increase due to SOIA that was quoted from the Draft Environmental Assessment for that project, the chapter on “Benefits of New Air Traffic Control Technology” contains no quantitative assessment of the potential capacity benefits of any of the technologies. However, as part of the RASP Update, a simulation analysis was performed of airport capacity and delay at the commercial airports in the region.[13] This analysis examined various runway reconfiguration alternatives at SFO, as well as a new air traffic control technology case in which reduced in-trail aircraft separations were assumed. The simulations were run for 1999 traffic levels as well as for projected traffic levels for 2010 and 2020. The simulations for 2010 and 2020 all assumed that the SOIA/PRM procedures would be in use at SFO during appropriate weather conditions.

According to the Bechtel report (p. 4-12), the SOIA procedures at SFO were not explicitly simulated. Rather, the simulation model was run for VFR and IFR conditions in West Plan flow and the proportion of the time that VFR conditions were assumed to exist was increased by 7 percent to allow for the two arrival streams during SOIA operations. Since SOIA procedures are only expected to increase the arrival rate to 38 aircraft per hour, rather than the 60 aircraft per hour during VFR conditions, this would appear to underestimate the delays in 2010 and 2020.

According to the simulation results presented in the Bechtel report, the reduced separations assumed for the new technology case reduced the weighted average delay for 2010 traffic levels from 17.02 minutes per operations to 14.75 minutes per operation. However, the changed in-trail separation assumptions are not stated in the report, so it is not possible to comment on their reasonableness.

Discussion

The descriptions of potential new air traffic control technologies contained in the RASP Update identifies the major technological components of any future air traffic management system, but by treating each of them as a separate system, largely fails to consider how they might be combined into an operational system that delivers significant gains in airport capacity. The discussion fails to mention the NASA Airborne Information for Lateral Separation (AILS) program that has been exploring the use of ADS-B to allow aircraft to self-separate under instrument conditions, much as they do today under visual conditions. The consideration of how these technologies might be applied at SFO is generally superficial, and while a number of difficult implementation issues are identified, there is no discussion of how these might be overcome, what this would involve, and how long this might take.

Although the airport capacity and delay simulation analysis presented in the RASP Update includes an assessment of the effect of new air traffic control technology, the details of how this was done are not discussed in the report. In any event, it does not appear that any consideration was given to new air traffic control technologies that would allow parallel instrument approaches to the existing runways, other than SOIA/PRM. Since the intersecting runways require gaps to be left in the arrival stream to allow departures to be released, there are limits to how much in-trail spacing can be reduced on final approach, and hence the capacity that can be achieved with a single arrival stream.

[13] Bechtel Infrastructure Corporation, *Regional Airport Capacity and Delay – Final Report*, Prepared for the Regional Airport Planning Committee, January 2001.

BCDC Consultant Review

A review of the EIR/EIS alternatives for the proposed SFO runway reconfiguration program was undertaken by G & C Aviation Consulting for BCDC.[14] This review examined two documents prepared as part of the EIR/EIS process in November 2000, one entitled "Alternatives Considered and Eliminated from Detailed Study" and one entitled "Demand Management Alternatives". The G & C report briefly discusses a number of air traffic control and aircraft navigation technologies, and provides a more extensive description of several other air traffic technologies in two appendices.

Technologies Considered

The report provides a brief summary of the following air traffic control and aircraft navigation systems:

- Center-TRACON Automation System (CTAS)
- Direct-To Solution
- Collaborative Arrival Planner (CAP)
- Surface Management System (SMS)
- Free Flight Phase 1 (FFP1)
- Area Navigation (RNAV)
- Inertial Navigation System (INS)
- Doppler Radar
- Flight Management System (FMS)

The descriptions of the four air traffic control systems (CTAS, Direct-To, CAP and SMS) are extremely brief, and the report fails to note that CAP and SMS are actually part of the CTAS program, and FFP1 is not a separate technology, but a program to deploy a number of automation tools, including SMS and other CTAS tools.

The appendices provide more detailed descriptions of the following aircraft navigation and air traffic control technologies:

- Global Positioning System (GPS)
- Wide Area Augmentation System (WAAS)
- Local Area Augmentation System (LAAS)
- Required Navigation Performance (RNP)
- Automatic Dependent Surveillance – Broadcast (ADS-B)
- Aircraft Vortex Spacing System (AVOSS)

[14] G & C Aviation Consulting, *A Review of the EIR/EIS Alternatives for the Proposed SFO Runway Reconfiguration Program*, Prepared for the San Francisco Bay Conservation and Development Commission, Interim Report, March 2001.

as well as brief summaries of the following air traffic control systems or concepts:

- Traffic Management Advisor (TMA)
- Final Approach Spacing Tool (FAST)
- Airborne Information for Lateral Spacing (AILS)

The discussion of TMA and FAST fails to explain that these are components of CTAS, rather than separate technologies. Although the report notes that AILS and AVOSS were both developed as NASA research programs, there is no discussion of what would be involved in deploying these concepts at SFO.

Capacity Benefits Assessment

The report makes no assessment of the capacity benefits that any of the technologies considered might provide at SFO. The report notes estimates of projected annual cost savings that have resulted from deployment of various CTAS tools at Atlanta and Dallas/Fort Worth International Airports, but does not discuss how those benefits might translate to the situation at SFO.

Discussion

While the report provides a useful checklist of potential air traffic control and aircraft navigation technologies, there is no consideration of how the various technologies might be applied at SFO, or indeed whether they would be of any use whatever. In particular, there is no discussion of the procedures that would have to be developed in order to enable any particular technology to result in a change in capacity, the steps that this would require, or how long these steps might require to be accomplished. Several of the technologies discussed (such as those being deployed under the Free Flight Phase 1 Program) address entirely different issues from the capacity problems at SFO, and at least one (Doppler radar) is an obsolete navigation technology that has been superseded by more modern technologies, such as GPS.

Other Studies

In addition, the Panel took into consideration relevant information from a number of other recent studies and plans. These are briefly discussed in this section.

National Airspace System Architecture, Version 4.0

The FAA National Airspace System Architecture, Version 4.0, represents the more recent version of the FAA's plan for the modernization of the National Airspace System (NAS).[15] The plans for the NAS modernization described in the NAS Architecture, Version 4.0 (NAS 4.0) are divided into three phases, with Phase 1 to be completed in 2002, Phase 2 to be completed in 2007, and Phase 3 extending through 2015. Many of the technologies discussed in the FAA/OER report described above (PRM, GPS/WAAS/LAAS, ADS-B, and CTAS) are envisaged in NAS 4.0 to be deployed to the field in varying states of completion by the end of 2007, with refinement and full operational capabilities extending through 2015. The future implementation plans represented by NAS 4.0 recognize that full technology implementation

[15] Federal Aviation Administration, *National Airspace System Architecture, Version 4.0*, Washington, D.C., January 1999.

timing is a function of end-user acceptance and equipage, as well as the draw-down of last-generation capabilities.

NAS Operational Evolution Plan

The recent release of the FAA NAS Operational Evolution Plan (OEP), Version 3.0, articulates the current FAA vision of how the NAS will evolve between 2001 and 2010.[16] It attempts to integrate and align planned FAA activities with those of NASA and the aviation industry, in order to address the growing imbalance between the demand for air travel and the capacity of the system. It recognizes that keeping pace with demand will require fundamental changes in operations, and addresses the mismatch between capacity and demand in four areas: airport arrival/departure rates, en-route congestion, airport weather conditions, and en route severe weather. The OEP recognizes the need to apply technology and procedures to retain use of closely spaced runways when deteriorating weather reduces airport arrival and departure rates (p. 9). However, beyond pursuing pilot acceptance of SOIA, the implementation of LAAS, and the use of cockpit displays for enhanced visual acquisition of nearby traffic, there is no discussion in the current version of the OEP of other steps that would be necessary to allow instrument approaches to closely spaced parallel runways. The current version of the OEP does envisage the deployment of the Single Center version of TMA at SFO.

FAA Airport Capacity Benchmark Report

Earlier this year the FAA released the results of an analysis of the current and projected future capacity at 31 of the nation's busiest airports, including SFO.[17] The analysis of future capacity considered any planned new runways and any technology and procedural improvements that were expected to be implemented by 2010. The analysis was performed for both visual approach conditions (termed optimum rate) and for instrument approaches (termed reduced rate). Only one weather condition and runway configuration was analyzed for each condition. No new runways were assumed for SFO, and the analysis of reduced rate capacity with new technologies and procedures did not include the effect of PRM/SOIA, because the assumed weather conditions for this analysis were below the minima for SOIA. The technology and procedural improvements that were considered included ADS-B/CDTI with LAAS and FMS/RNAV routes. However, the resulting capacity benchmarks only gave a 3 percent increase in reduced rate capacity due to these technologies and procedures and no increase in optimum rate capacity. The optimum rate capacity benchmark under current conditions gave a maximum arrival rate of 50 aircraft per hour, while the reduced rate capacity benchmark under current conditions gave a maximum arrival rate of 30 aircraft per hour.

Potential Impact of Changes in Technology on the Development of Air Transport in the U.K.

In November 2000, the United Kingdom (U.K.) Department of the Environment, Transport and the Regions published the final report of a study undertaken by Arthur D. Little Limited that examined technologies that might be available in the next 30 years that could

[16] Federal Aviation Administration, *National Airspace System Operational Evolution Plan*, Version 3.0, Washington, D.C., June 2001.
[17] Federal Aviation Administration, *Airport Capacity Benchmark Report 2001*, Washington, D.C., April 2001.

impact the development of air transport in the U.K.[18] The study included technologies that could enhance airport capacity, and identified factors that could influence the rate at which these technologies could be implemented and the implications for government policy. The study provides one of the most comprehensive summaries of potential capacity enhancing technologies that the Panel is aware of. However, the screening process adopted in the study eliminated many of the potential technologies from detailed consideration on the basis of a desktop review, the details of which are unclear from the report. The resulting technologies that were assessed as either very promising or promising do not include any that have not been considered by the other studies reviewed by the Panel.

Safety of Closely Spaced Parallel Approaches

A number of recent studies undertaken by researchers at the Department of Aeronautics and Astronautics at Stanford University have examined the safety requirements for operating simultaneous approaches to closely spaced parallel runways under IFR conditions.[19,20,21] These studies have addressed the aircraft navigation and flight management system performance requirements to safely operate paired approaches using LAAS enhanced ADS-B technology and maintain safe separation between aircraft in the event of a blunder (unexpected deviation from the correct course) by one aircraft in a pair.

Improved Weather Sensing and Data Fusion

A recent study by researchers at the Massachusetts Institute of Technology Lincoln Laboratory has analyzed the weather sensing and data fusion requirements to improve safety and reduce delays at a number of West Coast airports, including SFO.[22] The results of the study suggested that an augmented Integrated Terminal Weather System terminal winds product could provide very large delay reductions at SFO during winter storm conditions.

Public Input

The panel also considered an independent proposal submitted to the Airport by David Hooper entitled, *Alternative to San Francisco International Airport Runway Expansion.* The proposal suggested using differentially corrected GPS in combination with a moving map to help facilitate instrument landings to SFO's closely spaced parallel runways. The techniques are similar to WAAS and LAAS-based techniques, with ADS-B's Cockpit Display of Traffic Information (CDTI). The proposal did not address the requirements for accuracy, integrity, availability, and continuity of function placed on all public-use aviation navigation systems that

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[18] Arthur D. Little Limited, *Study into the Potential Impact of Changes in Technology on the Development of Air Transport in the UK*, Final Report to the Department of the Environment, Transport and the Regions, Cambridge, England, November 2000.
[19] Teo, Rodney, and Claire J. Tomlin, "Computing Provably Safe Aircraft to Aircraft Spacing for Closely Spaced Parallel Approaches," *Proceedings of the Digital Avionics Systems Conference (DASC00)*, Philadelphia, Pennsylvania, October 2000.
[20] Houck, Sharon W., *Multi Aircraft Dynamics, Navigation and Operation*, Ph.D. Dissertation, Department of Aeronautics and Astronautics, Stanford University, April 2001.
[21] Teo, Rodney, and Claire J. Tomlin, *Provably Safe Evasive Maneuvers against Blunders in Closely Spaced Parallel Approaches*, Paper AIAA 2001-4293, Presented at the AIAA Guidance, Navigation and Control Conference, Montreal, Canada, August 2001.
[22] Evans, J.E., *et al.*, *Weather Sensing and Data Fusion to Improve Safety and Reduce delays at Major West Coast Airports*, Project Report ATC-290, MIT Lincoln Laboratory, Lexington, Massachusetts, November 1999.

go beyond achievable position accuracy, and will be met by LAAS and WAAS-based systems, or the operational requirements for maintaining safe aircraft separation.

Summary

The previous studies related to the SFO Runway Reconfiguration Project reviewed in this section identified a number of potential technologies, summarized in Table 2-1. In many cases, a given technology was discussed by several, or all, of the studies, as shown in Table 2-1. As discussed in Section 1 above, the Panel believes that it is important to distinguish between deployable air traffic system enhancements and the underlying enabling technologies, such as navigation and communication systems. Two technologies mentioned in the previous studies address the design and capabilities of future aircraft that might use the airport and thus are considered separately from air traffic system enhancements.

Most of the studies that examined potential capacity enhancement technologies provided qualitative descriptions of the technologies, but did not attempt to quantify the likely impact of a given technology on the capacity of the airport. The only study that provided a quantitative assessment was the simulation analysis performed as part of the Regional Airport System Plan Update. However, while this presented an assessment of the reduction in delay, the report provided no information on the assumptions that went into the analysis, and thus it is impossible to assess the reasonableness of the results without further information.

The studies performed for SFO and FAA/OER include vague, qualitative statements about the likely timing of the technology becoming available, such as:

> "Closely-spaced parallel approach procedures and the ATC technologies to support them are still many years away from being realized. Development of these procedures will require a significant amount of time, particularly since several of the technologies … remain untested or undeveloped. Therefore, it is unlikely that these procedures will provide meaningful reductions in aircraft delays at SFO until the long-term future, if at all."[23]

While many of the technologies discussed in the studies will indeed take many years to put into operations, any runway reconfiguration is also many years away from being realized, given the time required for environmental review and construction. Without defining what constitutes a "significant amount of time", "meaningful reductions" or "the long-term future", such statements provide little useful guidance on how to assess the likely contribution of this technology or when such capacity gains might be achieved. It is also worth noting that the final phrase "if at all" suggests that there is some chance that the procedures and supporting technologies in question may never be realized. However, there is no discussion in the report of the basis for this statement or how great the chance is. The tone of the last sentence suggests that it may be quite high, but this is unsupported by any evidence in the report.

Similarly, the study performed for BCDC by G & C Aviation Consulting offers no assessment of either the potential capacity gain at SFO that might result from any particular technology or when those technologies that are not already being fielded might become available. Thus the study provides no more guidance on how much capacity might be increased through technology than the studies for SFO.

[23] P&D Aviation, *Analysis of SFIA Runway Reconfiguration Impact on Regional Air Transportation Systems, Working Paper No. 12: Delay Reduction Alternatives*, Oakland, California, March 1999, p. 3-7.

Table 2-1
Technologies Reviewed by Previous Studies

	P&D WP 7	P&D WP 12	FAA Report	RAPC Update	G&C Report
ATM System Enhancements					
1 PRM	x	x	x	x	
2 SOIA	x	x	x	x	
3 CTAS tools					
a Passive FAST	x	x	x	x	x
b Traffic Management Advisor	x	x	x		x
c Active FAST			x		
d Descent Advisor	x	x	x		
e Surface Movement Advisor			x		x
f Departure Planner			x		
4 AILS	x	x	x		x
5 AVOSS			x		x
6 Ground hold programs (CDM/CAP)	x	x			x
7 Free Flight Phase 1 tools					x
8 Direct-To tool					x
Enabling Technologies					
1 GPS			x		x
2 GPS enhanced by LAAS or WAAS	x	x	x	x	x
3 Required Navigation Performance			x	x	x
4 ADS-B			x	x	x
6 Wake vortex detection	x	x		x	
7 Area navigation (RNAV)					x
8 Inertial navigation systems (INS)					x
9 Doppler radar					x
10 Flight management systems (FMS)					x
11 Active noise reduction			x		
New Aircraft Technologies					
1 Wake vortex alleviation				x	
2 Civil tiltrotor aircraft			x		

In summary, the reports from studies done to date do not answer the fundamental question of how much the implementation of new air traffic management procedures, based on new ATC and aircraft navigation technologies, can be expected to increase the capacity of SFO, nor when those increases in capacity might be achievable.

3. OPERATIONAL CAPABILITIES REQUIRED TO INCREASE CAPACITY

The previous studies reviewed by the Panel have identified a range of future air traffic technologies that are either in the process of being deployed or are likely to be deployed within the time frame of concern. Some of these, such as ADS-B, represent enabling technologies that are needed to support more advanced operational concepts, while others, such as CTAS, represent operational systems that alone or in combination with other advanced operational systems could potentially increase the capacity of SFO. Notwithstanding the importance of this distinction, which the previous studies have generally failed to adequately consider, the Panel believes that the previous studies, taken together, have identified nearly all of those air traffic technologies that are likely to become available to support advanced operational concepts in the 2005 to 2015 time frame.

What the previous studies have not done as well is to consider how these enabling technologies might be combined into operational systems that could deliver increases in capacity at SFO. In a few cases, such as CTAS, this integration of technology and operational concept has already occurred. In others, such as the FAA Safe Flight 21 operational evaluation program, the operational concepts surrounding the use of ADS-B and cockpit displays are still being developed. Therefore, the approach taken by the Panel has been to identify a set of operational capabilities that on the one hand address the factors constraining the capacity at SFO and on the other hand require supporting technologies that appear likely to be available within the next five to fifteen years.

Discussions surrounding aviation technology often center on specific technologies as if the technology was an end in itself. To technology vendors and manufacturers this may be the case. But to aviation end-users – air carriers, airports, air traffic control service providers, the traveling public, and communities surrounding airports – new and emerging technologies are enablers to achieve operational end states inaccessible today. To address the challenges faced by increasing demand and finite capacity, operational capabilities must be introduced that achieve the goals of the traveling public – safe, reliable air service.

Operational Goals, Operational Capabilities, Enabling Technologies, and Operational Procedures

A set of challenges face high density airports worldwide. For example, one of the challenges is the need to increase the number of airplanes that can arrive at or depart from an airport per unit time. This challenge can be addressed through a number of **Operational Goals**, including:

- optimizing or reducing the distance between aircraft in trail
- optimizing or reducing the distance between aircraft laterally
- eliminating dependencies of intersecting runways

- eliminating dependencies of converging runways or flight paths
- eliminating dependencies between airports sharing adjacent airspace
- minimizing time on the runway (runway occupancy time)
- minimizing flight distance in the terminal area
- minimizing taxi time to/from gates.

The above *Operational Goals* must be achieved safely. In order to accomplish the efficiency enhancements implied in the above list, while maintaining or improving safety, a set of actions is required to achieve the above operational goals. These are termed **Operational Capabilities**. Operational capabilities combine **Enabling Technologies** with sets of **Operational Procedures** to allow beneficial aircraft operations.

For example, the familiar Instrument Landing System (ILS) Category I Precision Approach is part of an *Operating Capability* that achieves the *Operational Goal* of maximizing aircraft landings under conditions of extremely low ceilings and visibility. The *Enabling Technologies* for ILS include the localizer (LOC), glide slope (GS), marker beacons, Distance Measuring Equipment (DME), and in some cases, radar. Additional enabling technologies associated with ILS operating capabilities include approach lighting systems, runway lighting, Very High Frequency Omni-directional Ranging (VOR), and Non-directional Beacons (NDB). Airborne equipment in the form of receivers for LOC, GS, DME, VOR, and NDB also are enablers, as are various displays, flight directors, and autopilots. The ILS operating capability can only realize benefits when the enabling technologies are put to use through various *Operational Procedures*. These take the form of operations concepts, pilot-controller responsibilities, charted procedures, and operating rules and regulations that create an orderly understanding of roles, responsibilities, and responses to non-standard events.

Aircrews and controllers alike require operational concepts in the form of regulations, normal, irregular, and emergency procedures to safely and efficiently function in a future, modernized NAS. Any consideration of future capabilities must include development of procedures and operational concepts designed to address the broad operational goals cited above. To recap: *Operational Goals* address broad challenges facing the overall aviation transportation system; *Operational Capabilities* represent total systems to achieve the operational goals; and suites of *technologies* and *procedures* enable the operational capabilities.

The following are specific operational capabilities necessary to address the operational goals facing SFO. These operational capabilities will be designed around new and emerging technologies and procedures, and collectively represent the vehicle for actual accrual of benefits for safety enhancement, efficiency improvement, and delay reduction.

- GLS (LAAS) CAT II/III Precision Approaches - all runways
- RNAV transitions to short LAAS final approach segments
- RNP procedures including departures and arrivals
- Approach spacing optimization
- Approaches to closely spaced parallel runways, including Paired Approaches

- Approaches to, and landings on, intersecting runways
- Enhanced visual approaches
- Departure spacing optimization from a single runway
- Departure spacing optimization from intersecting runways
- Guided Rejected Landing Procedure (RLP)
- Reduced runway occupancy time
- Pilot in the loop taxi management and surface operations.

In keeping with the philosophy of attributing benefits to an improved operating capability, this section lists those improvements that will increase landing and takeoff rates, then breaks them down into the technologies required to enable those improvements. For each of the technologies, the mechanism is described that provides the improved operations as well as an assessment of when the capability might become operational at SFO.

There really are just two ways to increase the operations rate at an airport:

1) Increase the operations rate per runway
2) Operate on additional runways

At SFO today, when two runways are available for landing and two for departure, the airport can adequately keep up with the current schedule, even though the landings have a wake vortex dependency to observe, and the departures are dependent on both the landings and the adjacent departure. Thus, maintaining a “two-in, two-out” capability during periods with lower ceilings and visibility is desired. This is the simplest example of option 2) above, to maintain operations on more than one runway, using existing runways.

Enabling technologies necessary to achieve the above operating capabilities include:

- PRM/SOIA
- Global Positioning System - GPS
- Local Area Augmentation System – LAAS
- Automatic Dependent Surveillance–Broadcast – ADS-B
- High-Integrity Data Link(s)
- Wake Vortex Advisory System
- Center/TRACON Advisory System – CTAS

In addition to the enabling technologies listed above, the following airborne technologies are deemed essential to capturing NAS modernization benefits:

- Differential GPS receivers - Multi-Mode Receiver (MMR) with DGPS capability
- Cockpit Display of Traffic Information (CDTI) displays for enabling ADS-B

- Additional navigation software for specific applications such as Paired Approach procedures.

Table 3-1 lists the operational capabilities and associated enabling technologies applicable at SFO and within the Bay terminal area airspace.

Common to most of the above operating capabilities that can improve throughput at SFO are introduction of LAAS, ADS-B, and WVAS. Associated airborne equipage commonalities include the multi-mode receiver (MMR) for enabling LAAS data link approaches and piping of precise position, velocity and time (PVT) inputs to on-board systems, flight management systems (FMS), and a cockpit display of traffic information (CDTI) associated with ADS-B operations.

Table 3-1
Required Enabling Technologies for Different Operating Capabilities

Operating Capability	Enabling Technologies	Airborne Technologies
GLS (LAAS) CAT II/III Precision Approaches – All Runways	LAAS	MMR
RNAV Transitions to Short GLS Final Approach Segments	LAAS	FMS, MMR
RNAV Departures/Arrivals	Procedure Development	FMS
RNP Procedures	GPS, LAAS, WAAS, ADS-B	FMS, EGPWS, TCAS, CDTI
Approach Spacing Optimization	ADS-B, WVAS	FMS, CDTI
Closely-Spaced Parallel Approaches	LAAS, ADS-B, WVAS, RNP	FMS, RNP, MMR, CDTI
Paired Approach Instrument Approaches	LAAS, ADS-B, WVAS	FMS, MMR, CDTI
Enhanced Visual Approaches	ADS-B, Synthetic Vision	FMS, CDTI, HGS, Database
Guided Rejected Landing Procedure	LAAS, ADS-B	FMS, MMR, CDTI
Reduced Runway Occupancy Time	ADS-B	FMS, CDTI

In every case, operations concepts must be developed to allow air traffic control and aircrews to understand their roles and responsibilities with respect to each operating capability. Once operations concepts are developed, operating procedures must be developed that allow benefits to flow from the operating capabilities.

Most of the enabling technologies and airborne equipment are either already mature, or are in advanced stages of development. Exceptions include WVAS, with no current FAA funded development program, and synthetic vision capabilities. Components of WVAS and synthetic vision have been successfully demonstrated during recent NASA/FAA/industry demonstrations. The most significant roadblocks to NAS modernization accomplished through technology introduction remain FAA approval and certification of ground and airborne components, and stakeholder acceptance/buy-in of the improvements.

To insure timely availability of the above throughput-enhancements for San Francisco, widespread deployment of technology infrastructure must occur throughout the NAS. During a recent survey conducted at Chicago's O'Hare International Airport, 82% of all commercial aircraft were equipped with FMS RNAV capability. Though significant differences exist in FMS capabilities, basic RNAV operations are currently possible with a majority of aircraft operating at major airports. Though many of the aircraft are equipped to fly in an RNAV environment, and fleet equipage increases with each new aircraft in the fleet, airlines have historically not received "credit" for their avionics investments. That is, though most air carrier aircraft are now equipped with FMS/RNAV capabilities, the NAS is operated as it was over 30 years ago. This experience creates much of the reluctance to equip with next-generation capabilities such as GLS/MMR and CDTI, because the improved performance that can only be achieved through approved procedures remains in the hands of an uncommitted (and often unfunded) FAA. Therefore, air carriers' return on investment for buying-in to next-generation equipage is a risk the carriers have been unwilling to take. This creates a "chicken and egg" syndrome in which the operators wait for FAA commitment before deciding to equip their fleet, and FAA funding/commitment waits for widespread fleet equipage.

Fleet-wide equipage and aircrew training on approved procedures represents a cycle of nearly 5 years for major air carriers. This implies that if federal commitments and funding were guaranteed today, widespread accrual of delay reduction and capacity enhancements due to technology introduction would be realized by 2007. Unfortunately, most experts agree that a ten-year timeframe is more likely for benefit realization, due to the political processes involved in moving a system as complicated as the NAS forward.

Today's "first-come-first-served" strategy for handling aircraft arriving or departing into the terminal airspace, coupled with a reluctance on the part of air traffic control to change procedures until a vast majority of aircraft are equipped to participate helps precipitate the reluctance of industry to lead the technology introduction charge. That is, because "credit" cannot accrue to the *best* equipped aircraft until virtually all aircraft are equipped, it is most beneficial to be the *last* equipped, rather than the first equipped. One method to help accelerate the movement to next-generation operating capabilities (listed in Table 3-1) is to move from the first-come-first-served operating environment, to a "best equipped-first served" regime, crediting those operators who have invested in next-generation capabilities with less-constrained access to high-density terminal areas. This incentive to equip strategy allows the ten-year time frame (2011-2012) discussed above to be realized and planned for.

4. POTENTIAL TECHNOLOGIES TO ENHANCE SFO CAPACITY

The existing runway configuration at SFO presents two different operational constraints that potential air traffic technologies will need to address in order to have any significant effect on runway capacity. The first is the 750 ft spacing between the existing runway pairs and the second is the intersecting arrival and departure runways under most operational configurations. Unless a way can be found to allow two simultaneous arrival streams under IFR conditions, any potential capacity gains will be very limited. Similarly, the need to provide large enough gaps in the arrival stream to allow departures to be released limits the ability to reduce the spacing between arriving aircraft.

The proposed runway reconfiguration alternatives being considered present two different constraints. One is the effect of San Bruno Mountain on missed approach procedures by aircraft landing on the Runway 28 pair, and the other is the interaction of approaches to Runway 19R in Alternative F-2 with the final approach path to Runway 11 at Oakland International Airport. The former affects the location of the proposed new Runway 10L/28R and the latter affects the ability to utilize Runway 19R for arrivals under South East Plan flow. In addition, Alternatives A-3 and BX-2 retain the closely spaced runways in the north-south direction, and thus experience the same constraint as the existing runway configuration for arrivals in South East flow.

Technologies Considered for Further Analysis

The Panel identified the following four operational capabilities as representing the most promising ways to deploy new air traffic technologies to enhance the capacity of SFO for both the existing and proposed runway configurations:

- Use both closely spaced runways for arrivals in IFR
- Improve longitudinal spacing precision
- Reduce longitudinal spacing required to avoid wake vortex encounters
- Improve flight path precision for arrival and departure routes and missed approach procedures

The benefits of each of these concepts vary with the runway configuration. Two of the proposed runway reconfiguration alternatives include closely spaced parallel runways in the north-south direction, and all the proposed alternatives include some capacity constraints due to runway intersections. Therefore better management of longitudinal spacing and better coordination of operations on intersecting runways will enhance the capacity of all the alternatives. Improvements in the ability to predict the location and severity of aircraft wake vortices will both facilitate reductions in longitudinal separation, as well as provide enhanced safety for closely spaced parallel approaches. Finally, improvements in the precision with which aircraft can follow more complex arrival and departure routes will facilitate the separation of SFO arrival and departure flows from those to and from other airports in the region, particularly Oakland Airport.

In addition to enhancing the capacity of the existing or proposed runway configurations, new air traffic technologies that enable improved flight path precision may allow the positions of the runways to be modified in the reconfiguration alternatives in order to reduce the amount of

Bay fill involved. This could result from a reduction in the minimum separation between parallel runways without the loss of capacity that is experienced under current separation rules, or a relaxation of the missed approach requirements that could allow a new east-west runway to be located closer to San Bruno Mountain.

Use of Closely Spaced Parallel Runways in IFR

The use of the existing closely spaced parallel runways in IFR will require the deployment of new operational capabilities that can address the limitations that currently prevent such operations. The Panel has identified three operational capabilities that appear to offer significant promise to allow the use of both parallel runways under at least some IFR conditions:

- PRM/SOIA
- RNP Approach
- Paired Approach.

PRM/SOIA

Existing "Expanded Visual Approach Procedures" permit the two-in, two-out operation down to a ceiling of 3,500 feet and a visibility of 6 miles. It is proposed that the PRM/SOIA procedure will permit dual landings to continue down to a ceiling of 1,600 feet and a visibility of 4 miles. This procedure provides two converging precision approaches, both of which may be flown in Instrument Meteorological Condition (IMC) until the courses reach a minimum of 3,000 feet apart, laterally. From this point on, the approach is flown visually so that separation from the airplane on the adjacent approach, and its wake, can be accomplished by the pilot.

The design of this approach is such that the glide slope is at 1,100 feet at the missed approach point (3,000 feet between approach courses). Since the minimum ceiling is at 1,600 feet, the pilots will be in visual conditions for about 500 feet of descent, or something greater than 30 seconds, in order to visually locate the runway and the flight on the other approach. The pilots' union contends they need this much time to make the transition from instrument to visual conditions, locate the traffic, and prepare for the visual maneuver.

While the FAA is expected to approve the use of SOIA procedures down to a 1,600 feet ceiling, the resulting capacity gain will be dependent on the ability of ATC to "pair" the arrivals to prevent violation of wake turbulence avoidance criteria whenever the ceiling is below 2,100 feet. Part of the PRM/SOIA agreement is that ATC will sequence the two aircraft in each pair under these conditions so that the lead aircraft is in the same or a smaller weight category. This prevents achieving the full capacity of both runways. In a simulation run at the FAA's Bay TRACON, an average of 38 arrivals per hour was found to be achievable, up from 30 on a single runway, which represents a 27% increase in throughput over a single runway operation. This increase is available when the ceiling is between 3,500 and 1,600 feet, which has been estimated to occur between about 10 and 15% of the time.[24]

The technology panel made an assessment of weather conditions between 1945 and 1995 and determined that between 7 am and 11 am – when stratus conditions represent the most

[24] *Examining Technologies that Improve Operations in San Francisco*, Powerpoint presentation to the Independent Technology Panel prepared by Dave Jones, United Airlines, and Ken Peppard and George Greene, Federal Aviation Administration.

frequently limiting conditions – the ceiling and visibility are between 3,500 feet and 5 miles and 1,600 feet and 4 miles about 15% of the time; which is consistent with the estimates in previous studies. Therefore, the projected capacity increase from PRM/SOIA of 7 operations per hour is applicable for approximately 18 hours per month, on average.

RNP Approach

The time of dual operations can be increased if the approaches could be continued to a lower ceiling value. It is proposed that a RNP approach could be substituted for the SOIA with the advantage that it can be flown using the autopilot throughout most of the visual segment. This could reduce the pilot workload sufficiently to permit a shorter period for visual acquisition prior to the missed approach point at 1,100 feet on the glide slope. An operating ceiling of 1,300 feet might be acceptable under these conditions, still providing 15 seconds for visual acquisition of the runway and the other airplane. Wake vortex considerations still apply, but dual approaches could be maintained for perhaps an additional 3% of the time.

The RNP approach can only be flown by appropriately equipped aircraft and trained pilots, which would use the right hand approach. Assigning these aircraft to the RNP approach means that less than half of the aircraft population would need to be eligible, increasing the opportunities for pairs to twice the percentage of the eligible fleet, within the constraints of wake vortex avoidance. This means that the arrival rate under these conditions will steadily increase from 30 per hour to 38, as an increasing percentage of the fleet using SFO becomes equipped and approved to participate.

Paired Approach

A proposal to use the existing runways under all weather conditions is called the Paired Approach procedure. In this procedure, an ILS or GLS approach is made to one runway of a closely spaced pair of runways and a GLS approach following an RNP transition to short final is flown on the other approach. During that portion of the approach where the lateral spacing is less than 2,500 feet, the trailing aircraft in each pair is maintained in a longitudinal “window” that is based on the position of the leading aircraft in the pair. The leading edge of the window ensures adequate longitudinal separation to provide protection from a blunder by either aircraft, while the trailing edge is close enough to the lead aircraft to provide protection from the wake of the lead aircraft. Thus as more aircraft become suitably equipped and the flight crews are trained in the use of the procedure, increased use of both runways would be permitted in any ceiling and visibility condition.

In the paired approach concept, Automatic Dependent Surveillance - Broadcast (ADS-B) is used for air-to-air surveillance to establish the longitudinal “safe window” for the trailing aircraft, which would typically be on the upwind approach in the event of any crosswind to reduce the risk of encountering the wake of the lead aircraft. To accommodate different approach speeds on the final segment, the trailing aircraft would be flown so as to enter at either the front or the back of the box at the final approach fix, and drift toward the other limit as a function of final approach speed differential. The target airspeed of the lead aircraft could be determined verbally and entered by the crew of the trailing aircraft, or sent between aircraft as a data-link message.

The technologies to make the paired approach concept work are GPS with LAAS, GLS in aircraft, ADS-B, and the necessary software in the aircraft navigation system. Although not strictly necessary, the availability of a high integrity data link and WVAS will enhance the performance of the system and increase flight crew acceptance. The concept requires “precision approach” guidance to the autopilot during a gentle turning maneuver to final for Runway 28R. Although this capability for LAAS is desirable and possible, with curvilinear pathpoint data sent under high integrity conditions from the ground station, it is not included in “build one” of the LAAS offering. Higher minima paired approaches will be available using FMS guidance and LAAS PVT, but the instrument approach initially will be an RNP procedure, rather than a strictly defined precision approach.

The paired approach capability has been demonstrated in a simulation by the Mitre Corporation in their Integration Laboratory. But even a decision to proceed with the paired approach capability is unlikely to be taken for several years and operational use by a significant number of airplanes is probably at least five years beyond that. The use of ADS-B for air-to-air separation will require FAA approval of a major procedural change in an area they have yet to deal with. Because safety from collision and vortex encounter is built into this all-weather capability, the paired approach concept could permit an arrival rate close to a 60 aircraft per hour in any ceiling or visibility condition. This kind of major benefit might justify the necessary investments, especially as most of the systems would also have benefit at locations other than SFO. However, because of the significant coordination necessary to certify all required enabling technologies, the use of paired approaches on an operational basis may not be achievable before the 2010 to 2015 time frame.

Increasing Arrivals to a Single Runway

Another class of technologies is aimed at providing better longitudinal spacing precision between aircraft on the same approach, and between aircraft on adjacent parallel approaches. Even without changing minimum separation standards, a narrowing of the distribution of spacing intervals between airplanes produces an increase in the acceptance rate. Human controllers performing without spacing tools regularly average a 30-arrival rate on a single runway at SFO. With a spacing tool, this number could be increased to 34 or 35 while still permitting interleaved departures on the crossing runways. In the suite of controller automation tools developed by NASA and now being fielded by FAA, the Active Final Approach Spacing Tool or Active FAST is designed to provide controllers with this capability. An earlier version with less functionality called Passive FAST has been in operation at DFW for several years but does not perform the spacing function. In FAA’s plan, Active FAST is still 7-10 years from regular operations.

Passive FAST could be tailored to provide another function, that of determining runway assignment to properly pair aircraft for compliance with wake turbulence criteria. There is always some site-specific work done in each installation of pFAST, but it is unknown how much additional time or cost would be required to include this function. It is realistic to project that this capability would raise the PRM/SOIA acceptance rate from 38 to close to 45.

Another software tool already resident in the current terminal automation system is called the Converging Runway Display Aid or CRDA. This is generally used to help controllers interleave arrivals to crossing runways such that they do not meet at the runway intersection. In San Francisco, the tool could be used to more accurately pair aircraft on approach to the parallel runways by providing position and speed guidance to merge aircraft from different arrival fixes. As the objective is to get the airplanes nearly abeam each other on short final to minimize the interval between pairs, an aid to pairing can increase the efficiency marginally over what controllers do manually without such a tool. This could increase both arrival and departure rates during dual runway use by several (2 or 3) aircraft per hour during expanded visual operations.

Even tighter control over the longitudinal interval can be achieved by pilots (and autopilots) using ADS-B, even without the paired approach application. ADS-B surveillance using cockpit display of traffic information (CDTI) was demonstrated on multiple aircraft in the Ohio Valley trials of the Safe Flight 21 program in the summer of 2000. UPS, and perhaps other carriers in the Cargo Airline Association, has plans to equip their entire fleet with ADS-B and CDTI for this purpose and for collision avoidance. If their results are sufficiently positive it might persuade other carriers to follow suit. For there to be a significant impact on the acceptance rate at SFO, the dominant carriers at the airport would have to be equipped to participate. The limit to the single runway improvement from this technique would be the need to interleave crossing departures, and to maintain wake vortex separation between successive arrivals. The arrival rate using ADS-B and CDTI on a single runway might reach 36-37 per hour.

Another factor that causes the landing rate to drop below the theoretical maximum is the practice of separating airplanes by distance rather than time. The use of miles to define the required distance between airplanes on final approach comes from the use of radar by controllers to separate aircraft.

With separation defined in terms of distance, the actual time between successive landings, which relates directly to the hourly acceptance rate, depends upon the ground speed of the approaching airplanes. If the ground speed is 150 knots, a 3-mile spacing results in 1.2 minutes between arrivals, or a rate of 50 aircraft per hour for the runway. This is too fast at SFO to get departures out between arrivals, so a target of 4 miles on radar is used, resulting in a 37.5 rate. However, if the head wind on final is 30 knots, the ground speed drops to 120 knots, which at 4 miles results in 2 minutes between arrivals or a rate of 30 aircraft per hour. If a controller tool were available permitting the establishment of time spacing between airplanes rather than a certain distance on radar, then the wind no longer changes the time intervals between aircraft and the airport does as well on a windy day as on a calm one.

Wake Vortex Considerations

A fundamental limitation to the capacity of all runways, whether used alone or in parallel for arrival or departure, is the extra spacing provided to ensure that no wake vortex encounter will occur. The hazard of such an encounter can be catastrophic, if a smaller airplane gets into the vortex of a larger one near the ground. The strength of aircraft vortices is determined by the weight, the wingspan, and the speed of the generating aircraft with heavy and slow being the worst case.

Air traffic control provides extra separation for aircraft following one of a heavier weight category. This extra separation is designed to provide enough time for the vortex to dissipate prior to being encountered. The wake vortex separation standards are quite conservative and the safety record is good when they are used. Most of the time, however, the extra spacing is not necessary because the wake either has sunk below the flight path of the following aircraft, or has been blown out of the way by a crosswind. Also, if the air is turbulent, the vortices are broken up and dissipated long before the next airplane gets there. Heretofore, there has not been a means to guarantee the absence of the hazard, so the extra space is provided regardless of the actual vortex behavior.

Over the last nine years, NASA and FAA have performed research into the wake vortex problem with the intent of creating a system that can be used by ATC to provide the necessary separation from hazardous wake vortices, but re-capture most of the capacity lost to the blanket application of existing wake vortex separation standards. The results of this research have been quite promising. By making measurements of atmospheric conditions near the runway and in the approach and departure areas, it is possible to predict the movement and decay of aircraft wake vortices. Additionally, several sensors have shown promise of being able to detect and track vortex movement and even to estimate the strength of the vortex being tracked. NASA now is proposing a Wake Vortex Advisory System (WVAS) combining the predictive and measurement techniques to allow for stable increased traffic flows to an airport and still provide a safety net in the event a vortex does not follow its predicted path. The WVAS will be designed to address a number of operating scenarios, single runway arrivals and departures, dual closely spaced runway arrivals and departures, and crossing flight path situations. The dual arrivals and departures are particularly significant at SFO.

Current standards treat runways that are separated by less than 2500' laterally as a single runway for wake vortex purposes. That means that for aircraft to be paired on arrival or departure, one of two conditions must be met:

1) The lead airplane must be of a smaller weight category than the trailing airplane, requiring special sorting by ATC, or;
2) The pilots must see the other aircraft and accept responsibility for avoiding the wake of the other aircraft. This is what makes the current dual visual approaches work, but threatens the viability of the PRM/SOIA and other poor weather means for using both runways at SFO.

A successful WVAS could relieve both of these conditions, eliminating the requirement for ATC pairing of airplanes and freeing the pilots from the responsibility of wake avoidance under marginal visibility. When wind or atmospheric stability does not permit such nominal operations, the system would require ATC to use today's wake avoidance criteria.

The WVAS is still in development. If successfully fielded, it can raise the acceptance rate of the close parallels during SOIA/PRM to nearly the 60 rate of full visual procedures. Use of WVAS does not require any additional equipment on aircraft. Unfortunately, the development of WVAS is not complete and it could be five years or longer before full operational benefits could be realized.

Enabling Technologies

The foregoing operational capabilities depend upon the deployment of several enabling air traffic control and aircraft navigation and guidance technologies. This section discusses these technologies in more detail.

Local Area Augmentation System (LAAS)

LAAS is a highly accurate, high integrity augmentation to the basic GPS signal in space. Differential corrections to the basic GPS signal are required to insure aviation grade navigation in terms of accuracy, integrity, availability, and continuity of function. The LAAS signal is comprised of two parts – a correction message, and a navigation message establishing final approach segment guidance for all approaches within the LAAS service volume. The LAAS correction message is generated on the ground improving accuracy of the basic GPS position solution from approximately 15 to 20 meters to 1 meter.

Various checking mechanisms monitor the GPS constellation for availability and add integrity necessary for precision approach. Continuity of function is guaranteed through the LAAS signal to ensure a flight segment initiated can be completed with the required accuracy and integrity necessary for the operation. The LAAS navigation message sends pathpoints to the onboard Multi-Mode Receiver (MMR), where a path in space is constructed, and deviations from the desired path are sent to flight displays and the autopilot as ILS look-alike signals. The capability exists for the MMR to send augmented position, velocity, and time outputs to the FMS for precise navigation beyond the Final Approach Segment (FAS). In its initial state, LAAS will allow for straight final approach and missed approach segments, with pathpoints for straight segments being sent from the LAAS Ground Facility (LGF). Future states will provide other pathpoint constructions allowing complex geometry approaches and missed approaches.

Clearly, precise, stabilized, predictable and repeatable aircraft positioning is not the only factor allowing a move to VMC acceptance rates under IMC. Advanced surveillance, enabled by LAAS and achieved through Automatic Dependent Surveillance - Broadcast, is an attendant capability designed to address both airspace and ground-based movement needs. Collaborative decision making through common ADS-B surveillance information available to both ATC and aircrews - analogous to the see-and-avoid visual terminal operations described above - combine with predictable, repeatable flight paths to allow increased airspace efficiencies in high density terminal areas, when weather conditions preclude visual operations, and allow enhanced ground movement management with interacting aircraft and ground vehicles.

The LAAS Ground Facility utilizes a ground processing station, three (or more) GPS receivers, and a radio frequency transmitter to communicate via VHF data link. The LAAS receivers are accurately surveyed to precise tolerances, and determine corrections based on differences between known antenna positions and GPS-derived positions. These corrections are transmitted directly to aircraft via an RF data link, where on-board receivers merge raw satellite vehicle solutions with LAAS corrections to determine precise position fixes.

LAAS position accuracies are on the order of 0.6 to 1.2 meters, and allow aircraft to know their present position in space with greater precision than ever before, guaranteeing CAT I ILS minima, and also providing future capability for Category II (100 ft. decision height), and Category III A, B, and C approaches (with weather minima runway visual ranges of 700 feet, 100 feet, and autoland, respectively).

Short LAAS Final Approach Segments represent an opportunity for significant improvements in airspace flexibility. Traditionally, a precision final approach segment (FAS) began about 5 miles from the runway threshold, and an aircraft would need three or more miles beyond the FAS to become "established" safely. With the advent of augmented GPS sensor input to autopilots, and the availability of "guided" transitions to the FAS via Flight Management System computers and less sophisticated (but very accurate) GPS-coupled Area Navigation (RNAV) computers, the need for long, straight-in final approaches is waning.

Airline Operational Specifications typically require aircrews to be no lower than 1000 ft above ground level, in IMC, when they are wings level and established and engines spooled on the Final Approach Segment. Assuming a 3° precision glidepath to the runway, an aircraft is 1000 ft above touchdown at just inside 3 nautical miles (nm) from the runway threshold. Using the highly accurate LAAS Position/Velocity/Time (PVT) outputs available on properly equipped aircraft, will allow design of segmented RNAV guided transitions to LAAS precision final approach segments 3 NM from the approach threshold.

The multi-mode receiver accepts both LAAS correction messages and pathpoint data, allowing precision approach capability and significantly improved RNAV routing when LAAS-augmented PVT is sent to the FMS as the primary present position solution.

LAAS in San Francisco

Given the available accuracies and high integrity of the LAAS signal, many of the operational capabilities required for improved throughput and reduced delay are dependent on a LAAS signal at SFO. As noted in the FAA's *Airport Capacity Benchmark Report 2001*, LAAS is an integral enabler for any technological improvements at SFO. Clearly, LAAS will be a replacement for existing CAT I, II, and III ILS capabilities, but beyond precision approach, LAAS position, velocity, and time (PVT) augmentations to the basic GPS signal will allow predictable, repeatable paths throughout the Bay terminal area airspace.

At San Francisco, LAAS augmentation enables tighter RNP paths, allowing more flexibility in many operations, including lower minimums for SOIA approaches, reduced separation minima for parallel approaches and missed approaches, and the required integrity to allow ADS-B to become the approved first-order surveillance tool. As indicated in the Operational Capabilities table, most technological improvements necessary at SFO are dependent on both surveillance and a highly accurate, high integrity position to be broadcast.

Numerous studies and operational evaluations have indicated that LAAS input to advanced autopilots is a significant improvement over ILS in terms of accuracy, integrity, signal noise, etc. A recent study from Stanford (*Multi Aircraft Dynamics, Navigation, and Operation*, Sharon Houck, April, 2001) suggests that LAAS coupled with an advanced autopilot and ADS-B can reduce required spacing under IMC from 1,500 feet to 1,100 feet. Though this will not allow precision approaches to the existing runway configuration at SFO, it will allow lower minimums for RNP SOIA approaches, changes to no-transgression minima, and implies reduced separation minima for missed approaches. For the runway reconfiguration alternatives, this means existing missed approach protection surfaces can be revisited to allow properly equipped aircraft to operate in a guided, turning missed approach toward the San Bruno obstruction, without a penalty to the precision approach decision height for proposed Runway 10L/28R configurations.

As with other technology improvements, however, stakeholder buy-in, FAA commitment, and aircraft equipage remain issues influencing the timing of LAAS deployment NAS-wide. At Chicago O'Hare International and Memphis International Airports, commissioned and operationally approved LAAS facilities will be a reality by late 2002. However, aircraft equipped to operate against these systems will not be in-place for a number of years to come. FAA's deployment plan for LAAS includes a federal procurement starting in late 2003, with approximately 20 LAAS facilities installed over an eight to ten year period. Aircraft equipage is likely to lag LAAS deployment due to reluctance on the part of operators to equip until demonstrable NAS-wide benefits are available. Additionally, LAAS should not be considered an end in itself, but rather, part of a system including ADS-B functionality, RNP procedures and acceptance, and wake vortex advisory systems to allow the greatest operating flexibility, lowest minima, and greatest benefit accrual. With continued pressure from operators, industry, and airports, widespread LAAS/ADS-B/RNP availability is likely in the 2010 timeframe.

Automatic Dependent Surveillance – Broadcast (ADS-B)

Precise, stabilized, predictable, and repeatable aircraft positioning, available via LAAS and guided RNAV operations, are not the only factors advancing the move to improved acceptance rates under IMC. Advanced surveillance *enabled* by GPS/LAAS and achieved through *Automatic Dependent Surveillance - Broadcast* (ADS-B), is an integral program actively being pursued by FAA's Safe Flight 21 program, the Cargo Airline Association, Alaska's Capstone Program, and numerous large air carriers. ADS-B combines on-board, GPS-determined positions with two-way data link, to allow it to serve as the primary means of aircraft surveillance, as well as data messaging of other operational information. Collaborative decision-making through common ADS-B surveillance information available to both ATC and aircrews - analogous to efficient see-and-avoid visual terminal operations used today - will combine with predictable, repeatable flight paths to allow increased airspace efficiencies in high density terminal areas, when weather conditions preclude visual operations.

Radar and Surveillance

Historically, surveillance in aviation implied the action of an external entity determining the position and states of aircraft operating in an airspace. An aircraft's ability to determine its own position was not as efficient in ensuring its separation from other aircraft, obstacles to navigation, etc. Radio detection and ranging (radar) was introduced early in World War II to serve as a surveillance tool for unfriendly aircraft, in order to observe their movements and intent, and later to target and track those aircraft. During the Post-War era, enhancements to radar established it as the most important tool for establishing separations between aircraft in a rapidly expanding commercial aviation industry.

The advent of transponders on aircraft introduced the concept of aircraft participating in their collective surveillance and separation. A primary radar pulse illuminates an aircraft in space and "excites" the transponder to reply by sending its own active radar pulse from the aircraft. This secondary radar signal is modulated with discrete information from the sending aircraft such as a unique, identifying transponder code, and the aircraft present altitude. This secondary radar signal is much stronger than the reflected return of the primary radar pulse, and has enhanced air traffic control since the early 1960s. Aircraft equipage with secondary radar capability in the form of Mode C or Mode S is mandatory for aircraft to operate in high density terminal airspace, and most other controlled airspace. That is, today we have the concept of participating aircraft - those equipped with Mode C or Mode S, and non-participating aircraft that are prohibited from accessing certain busy airspace.

However, radar faces a number of limitations. Reflections of the signal make it a less than optimal surveillance tool for movements on the ground, and beamwidth spreading cause accuracy and target resolution to diminish with distance from the radar antenna.

In September 1993, the Global Positioning System constellation was fully deployed, providing continuous autonomous positioning anywhere on and in the vicinity of Earth. Like any signal-in-space, GPS was subject to an accumulation of errors, and faced purposeful degrading by the U.S. Department of Defense for national security reasons. Even with its error budget - guaranteed at a nominal 100 meter horizontal accuracy - GPS represented the highest accuracy positioning capability of any navigation source. With its augmentations - Local Area Augmentation System (LAAS) and Wide Area Augmentation System (WAAS) - differential GPS allows positioning with sub-meter accuracy in the case of LAAS, and 3-7 meter accuracies with WAAS. LAAS and WAAS also add requisite guarantees of integrity, availability, and continuity of function necessary for using the signal as a sole means navigation capability in the National Airspace System.

Automatic Dependent Surveillance

Automatic Dependent Surveillance-Broadcast (ADS-B) takes positions determined on board aircraft using GPS and its augmentations, and broadcasts those positions to other aircraft and ground receiving equipment. This first-order aircraft position is dependent on the accurate GPS positioning and timing capability. Clearly, the quality of the aircraft-derived position improves with DGPS, in the form of either LAAS or WAAS corrections. Therefore, ADS-B equipped aircraft and/or ground vehicles determine their positions, broadcast them, and receive similarly derived positions of other aircraft/vehicles within the service volume of the digital radio frequency (RF) transmissions. This information - including position, velocity, time of arrival, distance, trend vectors, etc. - is displayed on a moving map called a Cockpit Display of Traffic Information (CDTI). Ground stations also receive/transmit and display the positions, so that air traffic controllers and aircrews use common information. Aircraft and ground ADS-B stations use the same data link to receive information and to broadcast information. This two-way digital data link forms the surveillance basis of ADS-B. Therefore under the ADS-B scenario, participating aircraft and ground stations are sending and receiving position and other telemetry information to establish a highly resolute airspace and ground movement surveillance picture, and allows aircraft and ground-based collaborative participation in separation processes .

ADS-B ground stations can merge data from traditional radar sources with ADS-B information, display it, and transmit it to aircraft forming a complete air traffic picture. This data fusion capability is called a Traffic Information System (TIS). Given the digital nature of the data, automation of traffic alerts, alarms, and instructions can be broadcast to aircraft and ground vehicles to enhance safety and improve airspace and ground movement efficiencies. Regardless of the source of positioning information, ADS-B/CDTI, especially coupled with LAAS, provides a cockpit display of the location of other aircraft relative to “own” aircraft. This helps aircrews maintain relative position and desired separation from other aircraft more precisely.

ADS-B in San Francisco

Many of the Operating Capabilities important at SFO, leading to enhanced throughput and delay reduction, require ADS-B as an enabler. Because of the closely spaced parallel and intersecting runway environment at SFO, ADS-B with the most accurate positioning input (LAAS) is essential to any improvements with either existing infrastructure or proposed runway configuration changes. According to FAA’s *Airport Capacity Benchmark Report 2001*, released in February 2001, ADS-B and LAAS were common themes to any technology-related improvements at 31 of the Nation's busiest airports, including SFO.

Required Navigation Performance (RNP)

Required Navigation Performance is the minimum ability of an aircraft necessary to safely negotiate a flight segment in space. Obstacles likely to be encountered determine how accurately and precisely (repeatability) we must maneuver. An *obstacle-rich* environment is one that includes objects to be avoided - terrain, traditional obstructions (towers, buildings, etc.), other air traffic, or sensitive land uses. For aircraft flying en route, altitudes are generally high, and obstacles are limited - therefore, the highest accuracy/ precision positioning available is not necessary. That is, the *required* navigation capability or performance is less than during other, more critical phases of flight.

In the terminal area, because aircraft are operated closer to other aircraft, obstacles, and the ground, there is a need to maintain position more accurately, with a precision that allows repeatable performance, relative to predetermined paths. Consequently, the required overall navigation performance is higher than in the en route phase. The concept of maintaining aircraft position within increasingly smaller envelopes is central to Required Navigation Performance principles.

The combination of navigation signal arriving at the aircraft, the avionics available on board, and the type of steering engaged - manual raw data, flight director-aided, or autopilot - determine the ability of an aircraft to maintain a given path in space. Additionally, the phase of flight (approach, departure, terminal, en route, oceanic, etc.), imposes certain requirements on aircraft maneuvering. Thus, an airspace and phase of flight demand certain, required levels of performance in order that an aircraft function with optimized safety and efficiency. This required performance is quantified by establishing a volume around an aircraft that the aircraft must be contained within, and is a metric called *Required Navigation Performance* (RNP) - in length units of nautical mile (nm). If the combination of aircraft equipment, navigation signal used, and mode of flight operation allow the aircraft to meet the Required Navigation Performance for an airspace/phase of flight, that aircraft can safely operate to the lowest minimums supported by the given RNP.

For example if an aircraft desires to fly between two towers spaced 2 nm apart, to maintain the desired safety margin, current RNP specifications (RTCA's, *Minimum Aviation System Performance Standards: Required Navigation Performance for Area Navigation*, DO-236) suggests that the aircraft must have the ability to fly a desired path to 0.5 nm precision. An RNP philosophy to designing airspace is emerging that is a noticeable departure from past design strategies. Historically, design parameters for airspace operations were based on the least capable aircraft expected to operate in that airspace. Though this philosophy guaranteed safety margins for all aircraft, it penalized aircraft equipped with more advanced navigational equipment by not recognizing their improved capabilities.

Designing approaches and airspace capabilities with respect to the equipment available on board aircraft *and* the quality of navigation signals-in-space, is thus an RNP concept. Basically, if an aircraft's ability to maintain a desired path in space meets the Required Navigation Performance necessary to guarantee safety, then the aircraft is permitted to execute the [more flexible] maneuver. That is, if an aircraft's *Actual Navigation Performance* (ANP -

measured on-board the aircraft) meets the RNP for a particular flight segment, it can continue to lower minimums or fly closer to obstructions/other aircraft without adversely impacting the safety of flight. RNP will maintain/enhance safety and improve efficiency through increased airport access to runways currently unavailable during poor weather conditions or critical flight maneuvers such as missed approach.

RNP manages and defines the airspace so that user operational and economic benefits are realized without compromising safety. If aircraft equipped to operate in the lowest RNP airspace are rewarded with priority handling, or by allowing them to fly formerly visual approaches under IMC, this will provide users with incentives to equip and gain operating benefits.

Given that navigation sensor input and equipment status changes as a flight progresses, the concept of *Actual Navigation Performance* (ANP) must be considered. ANP at any time is a measure of the Total System Error experienced by the aircraft at that time. As long as ANP is better than RNP, an aircraft can negotiate RNP airspace or procedures.

RNP in San Francisco

For those aircraft properly equipped, an RNP RNAV approach procedure is being developed to help support dual stream operations under the West Plan to lower weather minimums. The idea includes any aircraft flying a 28L ILS, and an RNP-capable aircraft flying a SOIA-like approach to 28R. Using the RNP concepts highlighted above, an RNAV equipped aircraft on the right side (28R) can descend further and converge closer to the 28L localizer path, as a function of its Actual Navigation Performance at the time. The aircraft on 28L can continue to ILS minimums, and the aircraft on the 28R RNP/RNAV approach can descend and converge to a minimum determined by its ANP. (from *Proposed SFO RNAV 28R Approach Procedure, Procedure Development Project, RNP Release #1,* Alaska Airlines, May 2000)

Current PRM/SOIA approaches are planned to minimums of a 1,600 feet ceiling and 4 miles visibility, whereas for aircraft achieving actual navigation performance of 0.15 nm on the Runway 28R RNP/RNAV approach, a decision altitude of 1,028 feet is achievable. This increases the available time that dual traffic streams are available for arrivals to SFO.

Like all other technology considerations, aircraft equipage is a primary concern. Any considerations of delay reduction are a function of aircraft equipped and crews trained to execute maneuvers to the lowest theoretical minimums. Advanced FMS capabilities are required to operate in a low-minimums RNP environment, and thus achieve delay and throughput benefits. However, if an environment were established to give priority to properly equipped aircraft, this could provide an incentive to airlines to equip and participate.

To help achieve pilot union and ATC acceptance of lower separation operations, ADS-B with LAAS, coupled with Airborne Information for Lateral Spacing (AILS) algorithms must be considered. This system-based approach is much more favorable for gaining acceptance and achieving benefits, but requires more time than the ten-year projection, in order to insure all technologies are in place.

For the SFO Runway Reconfiguration consideration, RNP/RNAV can help address decision height minimums relative to the San Bruno obstruction. Assuming LAAS and ADS-B availability by the time the runway reconfiguration is in place, coupled RNP/RNAV guided missed approaches will allow RNP credit to the minimum certified by the FMS – currently 0.11 nm. Using the current RNP specification of a lateral spacing no less than two times the

RNP value, an aircraft on a guided missed approach using FMS guidance could come within 0.22 nm of the San Bruno obstruction. This quarter-mile separation must be explored in the build alternatives as an incentive for future aircraft equipage that must be started today.

<u>Head Up Guidance</u>

A final technology enhancement can be coupled with LAAS/ADS-B/RNP/RNAV. Greater operating flexibility can be achieved with "*credit*" given for Head-up Guidance System (HGS)-equipped aircraft. Many air carriers are already moving to HGS as a means to improve situational awareness and simplify aircraft operations. HGS improves aircrew situational awareness by providing an image of the runway environment generated on the Head-Up Display in the pilot's field of view - whether visibility out of the cockpit allows "seeing" the runway environment or not. However, the generated image's accuracy is only as good as the navigation sensor input to the HGS system. With highly stable and accurate LAAS signals available from a LAAS Ground Facility, the Head-up Guidance System can generate an image of the runway precisely where it is relative to the aircraft's position. Traditionally, aircrews peer through fog, snow, rain-streaked windshields, and other visibility restrictions, searching for approach lights to guide them while maneuvering to the runway. LAAS signals-in-space coupled with HGS can *substitute* for approach lights, achieving improved minimums and gaining credit for aircraft properly equipped to execute LAAS/HGS-aided precision approaches. RNP/RNAV routing and ADS-B complete a picture of optimized operations under either existing or proposed runway configurations at SFO.

Again, though greater and greater flexibility is achievable in the 10-year timeframe, wake vortex limitations and intersecting departures will not be addressed by LAAS, ADS-B, RNP/RNAV, or HGS.

5. CONCLUSIONS AND RECOMMENDATIONS

The Panel was asked to evaluate the prospects for air traffic management technology, airspace allocation, and aircraft navigation, control or communication technologies that could increase the capacity of SFO to reduce existing and projected flight delays and accommodate projected flight demand. The panel believes that technology related operational capabilities alone will not eliminate all existing and projected flight delays or fully accommodate long-term projected flight demand. As a practical matter, any reduction in projected flight delays will require a significant increase in the runway arrival capacity during poor weather conditions.

The Panel has identified a number of future air traffic management technologies that will enable operational capabilities that can increase the arrival capacity of SFO during poor weather conditions. These operational capabilities vary with respect to both the likely capacity increase that they can provide and the timing when they are likely to be available. Those operational capabilities that will become available between now and 2005 appear likely to offer only modest increases in capacity with the existing runway configuration. As additional operational capabilities become available further in the future, they will enable larger increases in capacity. Furthermore, with several of these technologies, the increase in capacity that they provide depends on the extent to which aircraft are equipped to take advantage of them and flight crews are trained in and able to fly the necessary procedures. Therefore the capacity increase that they provide will initially be fairly small, and will increase over time as more aircraft are equipped and flight crews able to take advantage of the procedures.

Even so, it does not appear that the operational capabilities that will become available between now and 2010 will close the gap between the good weather and poor weather capacity. At best, it appears that by 2010 the arrival capacity of the existing runway configuration might be increased to about 45 aircraft per hour from the current 30 aircraft per hour. However, this will only be possible for some poor weather conditions. For other weather conditions, the increase will be much less. More advanced operational capabilities that could become available in the 2010 to 2015 time frame offer the potential to further increase the poor weather arrival capacity of the existing runway configuration under a wider range of poor weather conditions. By 2015, it may be possible to achieve an arrival rate to closely spaced parallel runways of as many as 60 aircraft per hour under most poor weather conditions.

The operational capabilities and their associated enabling technologies that the Panel recommends be included in the environmental review of the Runway Reconfiguration Project differ for the No-Build and Build Alternatives, since two of the proposed operational capabilities are only relevant for closely spaced parallel runways. This distinction is not completely clean, since Build Alternatives A-3 and BX-2 retain the closely spaced parallel runways in the north/south direction. Since arrivals on the Runway 19 pair during Southeast Plan operations only occur a small percentage of the time, consideration should be given to whether the costs of implementing an operational capability that allows simultaneous instrument arrivals to both Runway 19L and 19R for Alternatives A-3 or BX-2 are justified by the delay reduction benefits. This cannot be determined without a much more detailed analysis than has been performed to date or the Panel had the time or resources to undertake. However, since Alternative A-3 involves the least amount of Bay fill of the Build Alternatives and Southeast Plan operations typically occur during winter storm conditions and can last all day, this would appear to be a critical factor in the evaluation of the Build Alternatives.

Operational Capabilities to be Included in the No-Build Alternative

The critical consideration in defining the operational capabilities to be included in the No-Build Alternative is the need to be able to significantly increase the arrival capacity during IFR conditions. As a practical matter, this involves enabling instrument arrivals to closely spaced parallel runways. The Panel is aware of only two operational capabilities that offer a realistic prospect of being able to achieve this: PRM/SOIA and the paired approach concept. The capacity of these two operational capabilities can be enhanced by two other operational capabilities: Required Navigation Performance and a wake vortex advisory system.

It should be noted that PRM/SOIA and the paired approach concept differ not only in the enabling technologies required, but also in their implementation time frame and the potential capacity increases that they offer. PRM/SOIA can be implemented in the immediate future, and can be expected to begin to give operational benefits in the 1 to 3 year time frame. However, the procedures can only be used during a relatively small percentage of the time, when the ceiling is between 1,600 feet and 3,500 feet, and not all aircraft are expected to be able to perform the procedure initially, which will limit the capacity increase even when it is being used. The paired approach concept will take much longer to implement, but offers the potential to be used in a much wider range of weather conditions and to potentially allow a greater increase in arrival capacity.

PRM/SOIA

SFO and FAA are currently in the process of installing a PRM and associated equipment, and establishing the necessary procedures to be able to operate SOIA procedures to Runways 28L and 28R under appropriate weather conditions. The proportion of arrivals that will be able to take advantage of this procedure will depend on airline efforts to train flight crews in the procedure, as well as the ability of Bay TRACON to assign aircraft to the two approaches in an optimal way. This will require advance knowledge of the ability of flight crews to accept a SOIA approach.

Required Navigation Performance

The use of RNP is expected to allow SOIA procedures to be performed with ceilings below 1,600 feet and to support missed approach procedures with the paired approach concept. The enabling technologies for the use of RNP procedures consist of a LAAS ground station at SFO and the relevant aircraft navigation and flight management capabilities. The development of the necessary RNP procedures can begin to take place once SOIA is in use and operational experience is being gained on how quickly flight crews flying the SOIA procedure can visually acquire the other aircraft.

The increase in capacity provided by RNP derives from the ability to perform SOIA procedures under a wider range of weather conditions. Estimates of the resulting reduction in delays will require an analysis that takes into consideration the frequency of occurrence of those weather conditions and the expected proportion of aircraft able to perform any given RNP procedure. It appears that RNP might allow the increase in arrival capacity enabled by the SOIA procedures, from the current 30 aircraft per hour to perhaps 38 per hour, to be achieved during about 3% more hours.

Paired Approach

The paired approach concept will require some additional equipment on participating aircraft beyond that required for RNP procedures, principally an enhanced cockpit display and modifications to the flight management system software to process the ADS-B signal from the other aircraft in the pair and drive the cockpit display. No additional ground equipment is required beyond that for the RNP procedure.

The delay reduction benefits from the paired approach concept will depend on the weather conditions in which it can be operated and the proportion of aircraft that are suitably equipped and have flight crew with the necessary training and willingness to perform the paired approach procedure. Since one aircraft in each pair is entirely passive, apart from needing to be equipped with ADS-B, the procedure will result in a significant increase in capacity with only moderate levels of aircraft equipped to perform the paired approach. The resulting capacity gains will depend on the ability of Bay TRACON to manage the traffic flow so as to take full advantage of those aircraft that are able to perform the procedure.

With the majority of aircraft equipped with ADS-B and at least half the aircraft equipped to fly the paired approach procedure and their flight crews trained in the procedure, it appears possible to achieve an arrival capacity to closely spaced parallel runways approaching 60 aircraft per hour in most instrument conditions. However, the necessary certification and approval of this procedure is unlikely to be accomplished much before 2010, and could take even longer, depending on the priority given to this by the FAA. The resulting capacity gains will depend on how quickly the airlines equip their aircraft and train their flight crews in the procedure. Since United Airlines and United Express account for such a large proportion of the flights at SFO, and have the most to gain from reducing the disruption to their schedule from flight delays during bad weather, even if these were the only aircraft able to fly the procedure initially, the increase in capacity would be significant. Even so, it may well take until 2015 or beyond before enough aircraft are equipped and flight crews trained to achieve an arrival capacity approaching 60 aircraft per hour on a consistent basis.

Wake Vortex Advisory System

The wake vortex advisory system would require the necessary ground-based sensors and decision-support tools to enable controllers at Bay TRACON to determine when required aircraft separations can be safely reduced and to advise the traffic flow managers of the resulting change in arrival acceptance rates. Additional capacity gains will result from the elimination of restrictions on aircraft pairs during SOIA or paired approach procedures due to wake turbulence considerations. This could increase arrival capacity using SOIA procedures to perhaps 45 aircraft per hour. The Panel believes that this operational capability can be available in the 2008 to 2012 time frame.

The capacity benefits of deploying a wake vortex advisory system are dependent on the runway configuration being operated. With arrivals to one runway of a closely spaced pair and departures on the other, significant gains in arrival rates can be achieved when the normal wake vortex separation standards do not need to be applied. The potential increase in arrival capacity will depend on the fleet mix and any runway occupancy time constraints. However, with departures on a crossing runway, the required gaps in the arrival stream to allow the departures to be released will reduce any potential capacity gains. Therefore analysis of the likely reduction in delays will need to consider both the proportion of time when the weather conditions will allow the aircraft separations to be reduced and optimal operating configuration of the airport in order to take full advantage of these reduced separations.

In addition to enabling greater arrival capacity, a wake vortex advisory system would also allow an improvement to departure rates at ceilings below 800 feet.

Increased Arrivals to a Single Runway

The deployment of CTAS tools and the use of ADS-B to enable aircraft to improve their spacing precision in trail can be expected to increase arrival rates to a single runway by about 2 or 3 aircraft per hour. These capabilities have been identified in the FAA *Operational Evolution Plan* and can be expected to become available in the 2008 to 2012 timeframe.

Operational Capabilities to be Included in the Build Alternatives

With the exception of arrivals to Runways 19L and 19R in Alternatives A-3 and BX-2, discussed above, the potential to increase the capacity of the Build Alternatives involves increasing arrival rates to independent runways. A critical consideration with Alternative F-2 is resolving the potential interaction between arrivals to the new Runway 19R and arrivals to Oakland Airport, so that both Runway 19L and 19R can be used for arrivals during Southeast Plan flow.

PRM/SOIA and Paired Approach

Subject to further analysis on the relevant costs and benefits, the operational capabilities provided by PRM/SOIA and the paired approach concept described above for the No-Build Alternative may also be applicable to the closely spaced north/south runway pair for Alternatives A-3 and BX-2. It is worth noting that the PRM equipment that is presently being installed for Runways 28L and 28R would not be required for those runways under either Alternative A-3 or BX-2 and thus would be available to be redeployed to serve Runways 19L and 19R at relatively little cost once the new runway was opened under either alternative. The paired approach concept requires no runway-specific equipment, apart from the possible need to upgrade the runway and approach lighting system to allow instrument approaches to both runways. Therefore this operational capability could be applied to Runways 19L and 19R as easily as to Runways 28L and 28R.

Required Navigation Performance

Apart from its use to increase the amount of time that SOIA procedures could be used on the north/south runway pairs for Alternatives A-3 and BX-2, RNP could also be used for guided missed approach procedures from Runway 28R to avoid San Bruno Mountain. This could allow the threshold location to be moved further west, reducing the amount of fill required. The allowable amount of any such threshold displacement would depend on FAA criteria for RNP guided missed approaches, which have not yet been finalized. RNP procedures would also most likely be required to define instrument approaches to Runway 19R in Alternative F-2 to eliminate airspace conflicts with approaches to Oakland Airport.

Wake Vortex Advisory System

A wake vortex advisory system would provide the same benefits to the Build Alternatives as to the No-Build Alternative, although the capacity increase for approaches to the new Runway 28R would be greater due to the elimination of the need to allow gaps in the arrival stream to release departures on the cross runways.

Increased Arrivals to a Single Runway

The same operational capabilities that can result in increased arrivals to a single runway will apply to the Build Alternatives as described above for the No-Build Alternative. However, in the case of the new Runway 28L, the increase in arrival capacity will be greater due to the elimination of the constraint imposed on the existing runways by the need to allow gaps in the arrival stream to release departures on the cross runways.

Further Studies

The Panel has identified the operational capabilities and enabling technologies that it believes offer reasonable promise to increase the capacity of both the existing and proposed runway configurations and that are realistic to pursue within the time frame that it has been asked to consider. Some of these capabilities will become available in the fairly near future, while other will take much longer to achieve. The Panel has also made a preliminary assessment of the potential increase in capacity that each of these operational capabilities may provide.

However, as noted earlier in this report, the capacity benefits from any given set of technologies depends on both the traffic characteristics at the time and the extent to which the aircraft fleet is equipped to take advantage of them and the flight crews are trained in and comfortable with the necessary procedures. Also as noted earlier in this report, there are significant uncertainties over when it is reasonable to expect particular operational capabilities will become available. Therefore an adequate assessment of the likely increase in capacity from any particular set of operational capabilities in some future year will require a much more detailed analysis than the Panel has had either the time or the resources to perform. Unfortunately, none of the previous studies that the Panel has reviewed have addressed the relevant issues in any detail, and in most cases have not addressed them at all.

In order that the potential contribution of future air traffic management technologies can be properly addressed in the EIS/EIR, a quantitative assessment of both the likely capacity benefits of the various operational capabilities identified by the Panel and the associated uncertainties will need to be made. This assessment could be undertaken as part of the EIS/EIR process and will need to consider the operational context within which the various technologies might be deployed as well as the extent to which the various technologies complement each other. The necessary analytical tools exist to undertake this assessment in a more rigorous way than has been attempted in the studies to date, and should be used. The issues are too important to depend on back-of-the-envelope calculations and educated guesswork.

Role of the Airport in Implementing New Technologies

The historical inability to modernize the National Airspace System (NAS) during the past 20 years should not be construed to imply that *another* twenty years is needed before new systems are in place and providing benefit. The Panel believes that greater user involvement in the implementation of new systems – including airports, air carriers, air traffic controller unions, and pilot unions – will positively impact implementation timelines as long as benefits accrue as soon as possible to those who participate. The Panel also believes that user implementation (ground and airborne components) must begin immediately with capabilities in their current state, in order to maintain or to better the timelines projected by the FAA, the Free Flight Select Committee(s), the International Civil Aviation Organization, and others.

The National Airspace System Architecture, Version 4.0 (NAS 4.0) represents the current FAA program to guide introduction of new technologies to address airspace capacity issues. The panel believes that with proper political and technical emphasis, NAS 4.0 provides a viable roadmap for phased technology implementation, and should be used as a basis for technology implementation assessment. The Panel recognizes that there is implementation risk, but believes that the advent of government/industry partnerships such as the *LAAS Government/Industry Partnership*, FAA's *Pilot Program to Permit Cost Sharing of NAS Modernization*, and *Safe Flight 21*, plus the emergence of airport involvement in NAS technology implementation, such as Chicago's *Chicago Airport System Strategic Technology Initiative* (CASSTI) program, will focus new resources on maintaining the schedules projected by FAA under the NAS 4.0 program. However, the NAS 4.0 schedule does not include WVAS-like capabilities until the 2010 timeframe, and the Panel believes that efforts should be made to field these capabilities earlier in order to achieve the potential benefits that could be obtained from optimized approach and departure spacing, reduced in-trail separation, and aircraft separation as a function of time rather than distance.

The Panel believes that SFO is in a strong position to take an active leadership role in the deployment of new air traffic management technologies, and that such actions will make a big difference in how quickly potential future capabilities become available. The Panel recommends that SFO formally engage in a strategic technology initiative to accelerate the deployment of new air traffic management technologies. The airport has already taken steps in this direction with the deployment of SOIA/PRM, and could become actively engaged in deploying other technologies as well. It would not be alone. Other airport authorities, including Chicago O'Hare, Dallas/Fort Worth and the Port Authority of New York and New Jersey, have initiated programs to develop and deploy new air traffic management technologies in cooperation with the FAA and NASA. Federal research and development funds are limited and have to be spread over many programs. The airport authorities are in a unique position to bring both financial and institutional resources to bear on developing and deploying the necessary technologies, and thereby advance deployment dates by many years.

This aspect becomes important in any assessment of what capacity benefits can be expected from new technologies at any point in the future. How quickly the necessary steps are taken to field any given capability will greatly depend on how determined the airport authority is to make it happen, and the resources that it is devoting to this effort. Therefore this needs to be considered in assessing the potential contribution of new air traffic management technologies to reducing delays at SFO.